

Control of Inverse Response Processes by Model Predictive Control (MPC)

by

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Lemma Dendena Tufa)

UNIVERSITI TEKNOLOGI PETRONAS

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SEPTEMBER 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NURUL AQILAH BINTI MOHD JIMMY WONG

ABSTRACT

Due to the presence of Right Half Plane (RHP) zeros in the system, inverse response processes becomes hard to be identified and controlled. It happens when two separate effects are taking place at the same time but in different direction. Although inverse response problem is not infrequent to occur in industry especially chemical process industry, not many researchers pay attention towards controlling and solving this problem. In this paper, the author aims to compare the performance of the Model Predictive Control (MPC), Proportional Integral Derivative (PID), and Simple Internal Model Control (SIMC) in producing satisfactory control output for inverse response processes. Under this main objective, the author specifies it into three sub objectives. The first one is to design a MPC, PID, and SIMC for typical inverse response process. The second one is to measure the performance of the various controllers for set-point tracking or servo problem and lastly to compare the performance of the designed controllers.

To ensure that all the objectives can be accomplished, proper methods need to be set and done throughout the progress of the project. To achieve objective 1, the author will make a proper selection on the type of controller to be used for this project and write the MATLAB coding for the selected controller, MPC, PID, and SIMC. It is crucial to identify the suitable methods and make a proper analysis on the performance of the controller. Three methods, Integral of Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time-weighted Absolute Error (ITAE) have been proposed in order to analyse and measure the performance of the designed controller. These methods will be further elaborated in the research methodology part of this paper. And in the end, to attain last objective, the author will compare the results of measurements based on set-point tracking condition.

This project principally covers the simulation analysis and project design where the author will accomplish most of the task by using the MATLAB software during the course of this project. In end of this project, the author determines that MPC provides the quickest response compared to PID and SIMC controller other than producing satisfactory overall performance and is suitable to be used to control an inverse response process. Not only that this project can achieve its objective within time constraint, it is also feasible as the project is easily understood and the software that will be used to design the controller is fairly available.

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Inverse response process is a process that occurs when two antagonistic effects occur at the core of the process, Pierre (2004). This indicates that the initial response of a dynamic is in the opposite direction to the final outcome with respect to the ultimate steady state value, Price (2003). Inverse response normally takes place when two separate effects are occurring at the same time, but with different directions and dynamics behaviour. The system is thus has two transfer functions that are coupled in parallel. Hence, the individual outputs can be added to obtain the inclusive response, Vidyasagar (1986). The response occur by initially goes in one direction as a transfer function overcomes the other one for small period of time and afterwards goes in the opposite way towards its steady state when the second transfer function overcomes the first one. The essential characteristic of the process with inverse response is that the process transfer function has one or an odd number of zeros in the open right half plane. A simple example of a zero right half of the plant (a RHP-zero) Waller and Nygardas (1975) is:

$$G = K \frac{\tau s + 1}{(\tau_1 + 1)(\tau_2 + 1)} \quad \tau < 0 \quad (1)$$

Systems which have inverse responses are problematic to control and thus require special attention. From the year 1962, analogue computer has been used to simulate processes having inverse response and to demonstrate the operation of the controlling instruments, Bernardo (1964). Numerous research papers have discussed the characteristics of an inverse-response process, such as Vidyasagar (1985), McWilliams and Sain (1989), and Bernardo (1994) according to Vidyasagar (1986).

Former researchers start to develop a better controlling model that can help to resolve this problem. Researches have led to more practical control system such as Smith Predictor scheme and Model Predictive controller that can provide a better solution in controlling inverse response.

1.2 Problem statement

The RHP-zero is also considered as part of a class of non-minimum phase (NMP) processes, Zhang and Youxian (2000). This non-minimum phase characteristic of the process affects the achievable close-loop performance because the controller operates on wrong sign information at the beginning time of the transient. Crucial restrictions in terms of achievable output performance occur in this process and the condition of perfect control cannot be achieved by any stable causal controller, Rosenbrock (1970). One important limitation due to the presence of RHP zero is the high gain instability. Another control limitation is associated with the bandwidth. These factors usually slow down tight process control, Linoya and Alpeter (1962).

There are a lot of different control configuration can be found in the industry nowadays. Some of the control configurations are Proportional, Integral and Derivative (PID) controller, Smith Predictor scheme, modified disturbance observer control scheme, state space method, Internal Model Control (IMC) and Model Predictive Control (MPC). Though there are numerous ways to control the inverse response, yet there are only two popular ways controlling such a plant in the past in the context of process control, Stephanopoulos (1984). The first one uses PID controller with Ziegler-Nichols tuning, Waller and Nygardas (2003) and the other one uses an inverse response compensator, Linoya and Alpeter (1962). Regrettably, both of these are

empirical approaches and cannot actually provide satisfactory performance, Scali and Rachid (1998).

So these, Scali and Rachid (1998) and also Zhang et al (2000) proposed a respectively an analytical design for inverse response processes without implementing the time delay. Principally, it is developed based on modern H_∞ theory of control. The controller that has been developed by these researchers can provide the suboptimal frequency domain performance. However, people start to pay attention on a more complex problem related with inverse response which is time delay or dead time. Luyben (2000) proposed a new tuning method for inverse response process with time delay where he incorporate the PI tuning constants and represent it as functions of positive zero τ_z plus dead time. However, same as PID controller, it is too empirical and produces large oscillatory and overshoot. In order to overcome this problem, Chien et al (2000) proposed a new tuning method which is derived from a direct synthesis controller design method. This type of tuning method still has its own problem where the controller parameter is not convenient to tuning for practice.

Hence, in order to provide a better control for inverse response processes in industry, the author will try to develop another controlling method which is MPC where this method can help to predict future response of the inverse process and take control action based from the prediction method.

1.3 Objective

1.3.1 Objective of final year project

The purpose of this final year project is to enable the final year bachelor degree of chemical engineering programme to develop a framework, which will enhance students' skills in the process of applying knowledge, expanding thoughts, solving problems independently and presenting findings through minimum guidance and supervision.

1.3.2 Objective of project

General objective of the project:

To compare the performance of Model Predictive Control (MPC), Proportional Integral Derivative (PID) Control, and Simple Internal Model Control (SIMC) for inverse response process.

There are three main specific objectives for the project entitled ‘Control of Inverse Response Processes by using Model Predictive Control’:

1. To design a Model Predictive Control (MPC), Proportional Integral Derivative (PID), and Simple Internal Model Control (SIMC) for typical inverse response process.
2. To measure the performance of the various controllers for set-point tracking or servo problem.
3. To compare the performance of the designed controllers.

1.4 Scope of study

Several tasks need to be completed in order to achieve the stipulated objective. This project is largely focusing more towards simulations, analysis and project design. Some of the processes in industries are difficult to control. This includes the inverse response process that occurs in the plant. Such processes with inverse response behaviour are very problematic to control. For this project, the author will be designing a controller which functions to control an inverse response process. There are several common types of controllers that are currently used by the manufacturer to control such response which are Proportional-Integral-Derivative (PID) tuning controller, Simple Internal Model Control (SIMC), Smith Predictor scheme and Model Predictive controller. However, the author project will be concentrating to the tuning and design of Model Predictive Controller. With the aid of MATLAB Simulink software, the author will

develop a controller and evaluate the controller's performance to be compared with other conventional types of controllers in industry.

1.5 Relevancy and feasibility of the project

This project is significant as it can lead towards the improvement of controlling the sophisticated inverse response process that currently occurs in plants. This project has been chosen as it is not too complex and it is considerably feasible. Appropriate planning and schedule must be obeyed in order to successfully accomplish this project in the given period. The engineering concept applied and skills needed to do this project is easily understood and capable enough that it can be accomplished parallel to the duration time that have been targeted. Moreover, the tools and software to be used for this project are readily available. It becomes a lot unproblematic as proper training and guidance have been given by the trainer and supervisor before and while performing the task.

CHAPTER 2

LITERATURE REVIEW

2.1 Conditions subsequent to inverse responses

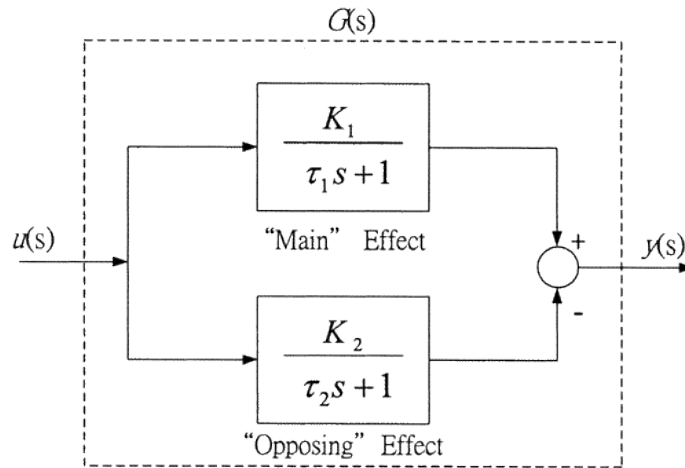


Figure 8: Block diagram of composite process (Source: Linoya & Alpeter (1962))

It is assumed that there are two opposing first –order stable processes:

$$G_1(s) = \frac{K_1}{\tau_1 s + 1}, \quad G_2(s) = \frac{K_2}{\tau_2 s + 1} \quad (6)$$

The value of K_1 , K_2 , τ_1 , and τ_2 are positive constant. If figure 1 shows a possibility of inverse response, the overall equations will be equal to:

$$y(s) = G(s). U(s) = (G_1(s) - G_2(s)). U(s) \quad (7)$$

or

$$y(s) = \frac{(K_1\tau_2 - K_2\tau_1)s + (K_1 - K_2)}{(\tau_1s + 1)(\tau_2s + 1)} \quad (8)$$

Where $G(s)$ is the overall transfer function, inverse response will occur when initially process 2 reacts faster than process 1 dominate the response of the overall system. However, process 1 reaches a higher steady state value than process 2 and start to forces the overall systems in the opposite direction as shown in the figure 7.

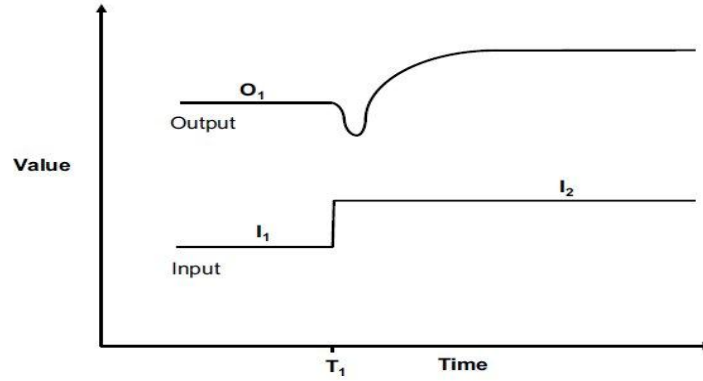


Figure 9-22. Inverse Response Process

Figure 9: Inverse Response behaviour (Source: <http://modelingandcontrol.com>)

Equation (5) indicates the system transfer function that has a zero in the open right half plane (RHP) [15]:

$$Z = \frac{K_2 - K_1}{K_1\tau_2 - K_2\tau_1} > 0 \quad (9)$$

2.2 Inverse response processes

2.2.1 Tray composition of a distillation column to variations in vapour flow rate

The responses that occur at the bottom composition and base level with respect to change in vapour boil up can indicate an inverse behaviour. It is known that in

binary distillation column, an increment that occur in vapour boilup, V must drive more low boiling material up the column. This will thus result the mole fraction of light key component in the bottom part, X_B to be decreased. This phenomenon eventually can cause the tray hydraulics to create an unexpected result. When a vapour rate that passes through the column is increased, it has a tendency to back up more liquid in the downcomer in order to resolve the increase in pressure drop through the tray. This will cause the liquid flow rate to be momentarily reduced while the liquid holdup in the downcomer is building up. Other than that, the increases in vapour rate also causes the density of the liquid and vapour that is on the active part of the tray to be decreased where it tends to momentarily increase the liquid rates since there is more height over weir. The opposing effect that will dominate others depends on the operating level and the tray design itself. When the pressure drops through the valve trays has a small effect with the change in vapour rates, the second effect tends to overcome the first effect. If this occurs, the rise in vapour boilup ratio causes a transient increase in liquid rates down the distillation column. The increment carries material which is dominant in light component into the reboiler and temporarily increases X_B . In the end, after some time, the liquid rates will turn back to normal when the liquid inventory on trays reached to the new steady state levels.

2.2.2 Level of drum boiler to variations in the heating medium flow rate

The rapid and vigorous effect of a heating medium flow rate or a steam pressure flow rate increase is to spill liquid off trays above the reboiler as soon as the vapour flow starts to increase. The slower effect is to remove significant amounts of the liquid mixture out of the reboiler through increased boiling. This will thus, causes the relationship between reboiler level and reboiler steam pressure to affect each other and can be represented approximately as an over-damped second order transfer function with an inverse response or right-half plane (RHP) zero.

2.2.3 Exit temperature of a tubular exothermic reactor to changes in the inlet reactant temperature

A tubular catalytic reactor with an exothermic chemical reaction can exhibit inverse response behaviour in the exit temperature when the temperature of the feed changes either increase or decrease. At the beginning of the process, the increased conversion in the entering section of the bed will momentarily depletes reactants at the exit end of the bed. This effect will hence causing less heat generation at that corner and make the temperature at the exit of the tubular catalytic reactor to decrease. Subsequently, reaction rate will increase and causing to a higher exit temperature as would be expected. On the other hand, when the feed temperature is decreased, inverse response will initially yields a much higher exit temperature before it reaches a new steady state.

2.2.4 Recycling of energy and material to a reactor makes poles and zeros move to the right half plane

In an integrated plant with material and energy recycling, the behaviour of a process unit may vary from other unit that is operated in isolation mode. Since the material and energy recycle is related to a feedback mechanism, linear system theory has been utilized to analyse the effect of recycling system on both poles and disturbance sensitivity. The recycling effect causes the poles of the plant to move towards and possibly across the imaginary axis. Hence, it will characteristically increase the time for a process unit to respond and at the same time increase the low-frequency disturbance sensitivity. Feedback executed by recycling hence, be likened to partial feedback in multivariable control systems. Jacobsen (1999) has proven how the partial feedback may cause the movement of both zeros and poles of the transfer functions and matrices in between inputs and outputs where they are not part of the recycling loop.

2.3 Case Study

The temperature of the municipal waste incinerator to variations in inlet load rate

Inverse Response Process in Municipal Incineration Plant, Germany

Inverse response can occur in several types of processes. This type of behaviour can be demonstrated by processes such as exit temperature of exothermic reactor to deviates in the inlet reactant temperature, the level of a drum boiler to variations in the heating medium flow rate, and also in the tray composition of the distillation column to variations in the flow rate of the vapour. Other than that, recycle process of energy and material to a reactor also makes poles and zeros to move to the right half plant (RHP). The temperature variation of the municipal waste incinerator that relates to inlet load rate also is considered as one of the process that can exhibit inverse response behaviour.

The municipal waste incineration plant was examined by M. Rovaglio where the plant is constituted by a primary combustion kiln. The contaminant product destruction is the completed by the post combustion chamber which is located after primary combustion. The plant is fed with an outlet hot gas to a power production system of 3 megawatt (MW).

Table. 1 Some technical data characterizing the examined incineration plant

<i>Primary kiln and postcombustion chamber</i>	
Thermal power capacity	20.4 MW
Municipal waste burning capacity	8.4 t/h
Total grid surface	35.5 m ²
Total smokes flowrate	53000 N m ³ /h
Postcombustion chamber volume	131 m ³
Combustion temperature	950–1250°C
<i>Boiler</i>	
Steam flowrate (max)	23 t/h
Steam temperature	360°C
Steam pressure	40 bar
<i>Heat recovery</i>	
Turbine power production	3.25 MW

Figure 10: Details of plant (Source:M.Rovaglio)

There are two main output variables in hot sections of the incinerator. The first one is the gas temperature and the other one is the content of oxygen in the outlet gas that comes

from the post combustion chamber. The direct effect of output variable can be adjusted to the set point by controlling manipulated variables which are the waste inlet flow rate and the air flow rate. The waste distribution that is varying in revolution speed can be controlled by the kiln that has a grid structure together with downwards and rotating drums. The schematic diagram of the plant is shown in figure 4 below:

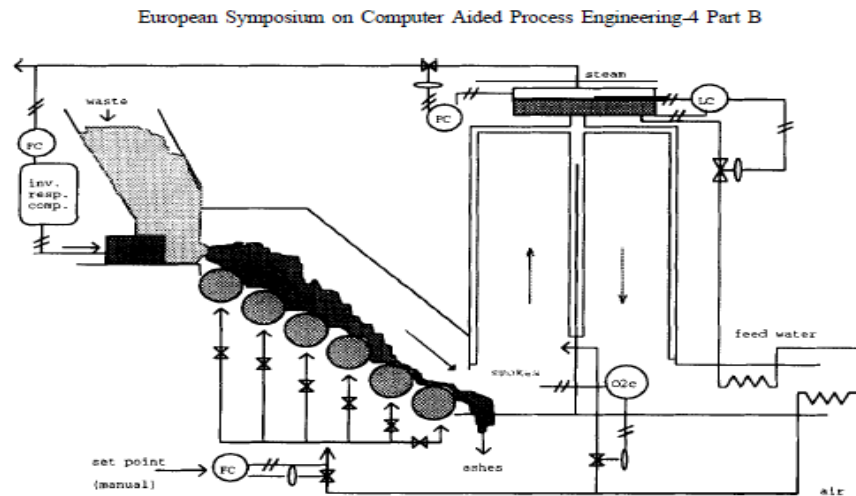


Figure 11: Hot section of incineration plant (Source: *M.Rovaglia*)

In order for the turbine engine to perform effectively, it needs constant and uniform operating conditions hence, making the control of steam flow rate to be very crucial. Undesirably, the secondary effect or disturbance is always present causing the output to deviate from its set point. The secondary effect is also known as inverse response. In simple terms, when the flow rate of the waste water is increased, the steam flow rate will not immediately increase to the set point. Instead, the flow rate will decrease for a while before inverting the trend and reaching greater value than set point at the end of the transient. The second effect occurs due to moisture and inert contents in the waste fed to the kiln that disturb the internal combustion temperature. Thus, the process will take several minutes before the waste can reach higher temperature so as to ensure the combustion mechanism can proceed effectively.

Conversely, when the flow rate of the steam starts to decrease, the corresponding feedback control loop will send a signal to the valve and increase the waste feeder speed. As a result of inverse response, the system will react oppositely by decreasing the steam flow rate and at the same time, further increase the feed flow rate where large amount of waste accumulated into the kiln starts to burn and producing numerous extent of heat. This will then causes the flow rate of the steam to be further increase to values higher than the desired set point. The process will oscillate, after a long time, reaching low temperatures and sudden hot spots.

2.4 Conventional methods to control inverse response process

2.4.1 PID controller

The traditional method, PID controller with Ziegler-Nichols tuning has been widely known since the past decade to control the inverse response process. Some of the research proves numerically that the Ziegler-Nichols classical tuning of PID controller could possibly yield good control for systems with inverse response. Waller and Nygardas(1962) have demonstrated that a PID controller with Ziegler-Nichols tuning is considered as an acceptable way in controlling the inverse response process. Some of the researchers such as Luyben (2000) even come out with a new tuning method like proportional-integral (PI) method in which the PI tuning parameters are functions of RHP zero and time delay. Conversely, the PI setting is empirical and causes instability which is large oscillation and overshoots. Chien et al. (2003) derived a PID tuning method from a direct synthesis controller design method, which does smooth and more stable output response. Due to the positive feature of the derivative action in the wrong direction of the system response, good results are able to achieve by PID controller. Regrettably, the PID controller parameters are not easy to be adjusted to actually reach and maintain stability margin. On the other hand, another controlling method, internal model control (IMC) design makes it possible to expediently adjust the system's robustness by using a single

tuning parameter. Comparatively few studies still argue on the control design for integrating processes with inverse response and time delay.

2.4.2 Smith predictor scheme (dead time compensator)

The smith predictor scheme also known as inverse or dead time compensator is used to control the process with an extended time delay to the control of processes with inverse response Chien et al. (2003). A new H_∞ design method presented by Doyle et al. (1992), Zhang et al. (1999), and Zhang and Sun (1997) are used for designing a controller analytically. Linoya and Alpeter (1962) utilized the concept of Smith predictor to cope with the inverse response process and hence proposed a compensation scheme denoted as inverse response compensator Linoya and Alpeter (1962). In Harriott's (1964) words "the purpose is to make the input to the controller the same as if the process had no time delay, which permits a much higher gain and reset rate to be used", Zhang & Youxian (2000). However, the statement mentioned must not lead one to conclude that a tighter controller tuning necessarily would imply better control for the output. With the incorporation of smith predictor scheme in system control, the effect of time delay of the process itself can be eliminated.

2.4.3 Modified disturbance observer control scheme

The disturbance observer is an often-used control method on motion control field. This controlling method was first developed by Ohnishi in the year 1987. Disturbance observer is very important to analyse the behaviour of disturbance and eliminate the effect of the disturbances while controlling the process. Studies have come out with a new load torque observer that takes the effects of system delay into the consideration that was proposed. Modified disturbance observer is commonly used to control the processes with the inverse response that has a long dead time. This controller will control the difficult inverse response by first rejecting the step disturbance together with ramp disturbance.

2.5 Skogestad/Simple Internal Model Control (SIMC)

SIMC-PID tuning method was developed based on previous work including the paper by Ziegler & Nichols (1942), the IMC-PID tuning paper by Rivera et al. (1986), and also the closely related direct synthesis tuning rules in the book by Smith & Corripio (1985). There are rather some drawbacks from the design of PID control alone. Even though Ziegler Nichols tuning method result in a very good load response for integrating processes, this method also result in rather aggressive settings (Tyreus & Luyben, 1992; Astrom & Hagglund 1995) other than delivering poor performance for processes with dominant delay. IMC-settings by Rivera et al. (1986) on the other hand will produce a poor disturbance response for integrating processes, Chien et al. (1990). IMC settings however, helps a lot in producing robust output and are very good for set point changes.

SIMC provides a better and easier tuning method in the form of PID controller. There are basically two steps procedures in constructing SIMC system. The first one is by obtaining a first or second order plus time delay function by using proposed half-rule. After that, a model in the form of PID will be derived based on the obtained first or second order plus time delay where PI is developed from first order plus time delay function and PID is from second order plus time delay function.

2.6 Model Predictive Control (MPC)

This type of control is of an open nature, within which many works have been developed and are widely received by the academic world and industry. The main motive of MPC is to find the input signal that best represents to some criterion which predicts the behaviour of a system in the future after applying this signal. The problem is then converted to mathematical model at a given state before solving the problem at each sampling time by using only the current control horizon which is known as Receding horizon technique. MPC can be divided into three main components which are the process model, cost function, and the optimizer. The model of the process includes the information regarding

the controlled process and will be used to predict the future response of the process values according to manipulated and controlled variables. Subsequently, after the minimization of cost function will ensure that the error is reduced. In the last step, diverse optimization techniques are applied and the output produces an input sequence that will be used for predicting the next prediction horizon. Figure below illustrates a basic structure on how the MPC works:

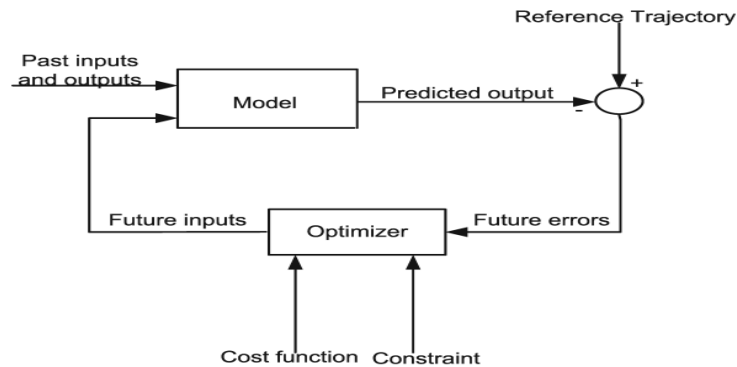


Figure 12: Basic structure MPC (Source: <http://ethesis.nitrkl.ac.in>)

There are various MPC algorithms that can be used and they differ among themselves in the model used to represent the process and the noises and cost function to be minimized. One of the MPC algorithms that is chosen to be used in this project is Dynamic Matrix Control (DMC) where this model uses step response as a plant model to predict future output of the plant. The DMC algorithm was first developed by Shell Oil engineers in late 1970's and was intended for used in petroleum refineries. Using DMC, the current control action is obtained by solving a finite horizon of open loop optimal control problem using current state of the plant as the initial state. This is done repeatedly for each sampling point to ensure that future prediction is done accurately. The optimization produces an optimal control sequence and the first control in this sequence is used and applied for the next prediction. DMC is very useful in controlling inverse response process as the models which are used will determine the behaviour of complex dynamical systems. These models tend to compensate for the effect of nonlinearities that is present in the variables and the chasm caused by non-coherent process devolution. Henceforth the models are

used as a prediction for the behaviour of dependent variables or outputs of the modelled dynamical system with respect to changes in the process independent variables or inputs. The objective of DMC is to drive the output as close as possible by using a least-square sense where there is a possibility of the inclusion of a penalty term on the input moves.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

Model predictive control (MPC) is broadly used multivariable control algorithm in the chemical process industries and other areas. MPC is suitable to be applied to almost any kind of problem. Still, it displays its main strength when applied to problems related with a large number of manipulated and control variable, constraints impose on both manipulated and controlled variables, changing control objectives or sudden equipment failure, and systems related with time delay. In general, MPC actually represents the behaviour of complex dynamical systems.

At the beginning of the project, the author is exposed to the MATLAB software Simulink to ensure that the author becomes familiarize with this software. Before being able to derive the controlling method for inverse response process, the author has to understand deeply and experience herself the difficulty to control an inverse response process without a proper controller. By tools in MATLAB Simulink, the author will then develop the process model that has been reviewed from actual incineration plant in Germany that yields an inverse response. Once the process is developed, author will be spending most of time to come out with the best controlling method with the least time delay and stable process by using tools available in MATLAB Simulink.

After determining the best controlling method using MPC which is DMC, the author will need to develop the currently used PID controller and SIMC by using the same software and compare the result with MPC method. The performance of each controller for set point change is then evaluated based on the time delay, stability, and behaviour of the controller itself.

In order to attain the first specific objective that has been specified before, the author will first have to select an appropriate type of MPC to be used and write the MATLAB code for the controllers chosen which are DMC of MPC, PID Ziegler-Nichols tuning method, and SIMC tuning method. On the other hand, to accomplish the second objective, the author will use three methods which are Integral of Absolute Error (IAE), Integral of squared Error (ISE) and Integral of Time-weighted Absolute Error (ITAE) where of these methods is used for different purposes. ISE criterion tends to penalizes large errors. This will be certainly useful for those who concern about the overshoot error that occur in the output of the system. Conversely, ITAE criterion penalizes errors that persist for long periods of time. This method should be chosen for those who want to compare the performance of controller with respect to time delay. In general, ITAE is prefers criterion as it usually results in the most conservative controller settings. By contrast, the ISE criterion has a tendency to provide the most aggressive settings while IAE criterion tends to produce controller settings that are between those for the ITAE and ISE criteria. For those who could not tolerate the overshoot and long-time error, IAE criterion assessment method will be most preferable and should be chosen. To achieve the last objective, the author will have to compare results from the measurement for set-point tracking. The value of integral error can be easily measured by using MATLAB software where no complex integration is required to obtain the area under the curve. However, the author still need to design the error calculation by using MATLAB coding as it will be easier for later use and proper for this specific project. For manual calculation, the formula below will be used:

$$IAE = \int_0^{\infty} |e(t)| dt \quad \dots\dots\dots(10)$$

$$ISE = \int_0^{\infty} e(t)^2 dt \quad \dots\dots\dots(11)$$

$$ITAE = \int_0^{\infty} t|e(t)| dt \quad \dots\dots\dots(12)$$

3.2 Developing a process model (Municipal Incineration Plant, Germany) using MATLAB Simulink

Based from the model synthesis and experiment validation conducted on the actual municipal incineration plant, M. Rovaglio (1995) has developed a non-linear model together with linear model of the plant itself. “The behaviour of the system in terms of steam flow rate, can be represented in terms of two opposing first order systems”, Linoya and Alpeter (1962).

$$G(s) = \frac{K_1}{\tau_1 s + 1} - \frac{K_2}{\tau_2 s + 1} \quad (13)$$

The gains and time constants of the municipal incineration plant can be derived from simulations through the detailed model in figure 4:

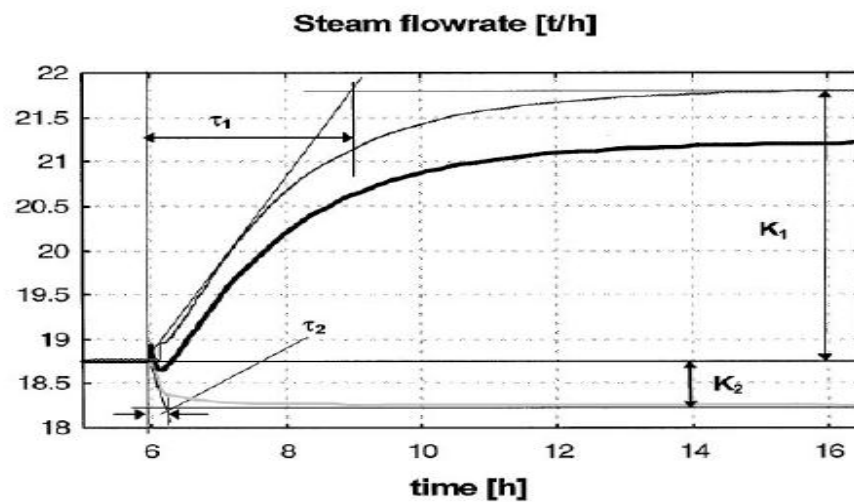


Figure 13: Direct and inverse effects on the steam flow rate (Source: M. Rovaglio)

From the graph,

$$\tau_1 = 3 \quad \tau_2 = 0.3$$

$$K_1 = 3 \quad K_2 = 0.5$$

Inserting the value into equation (13),

$$G(s) = \frac{3}{3s+1} - \frac{0.5}{0.3s+1} \quad (14)$$

Further details, comments, and discussions related to the mathematical model of the municipal incinerator plant adopted can be found in other technical paper from Rovaglio et al (1995).

$$G(s) = \frac{(K_1\tau_2 - K_2\tau_1)s + (K_1 - K_2)}{(\tau_1s+1)(\tau_2s+1)} \quad (15)$$

Simplified into:

$$G(s) = \frac{-0.6s+2.5}{(3s+1)(0.3s+1)} \quad (16)$$

The transfer function derived before is then tested by making a step change in the set point using MATLAB Simulink to ensure that the model is actually producing inverse response behaviour.

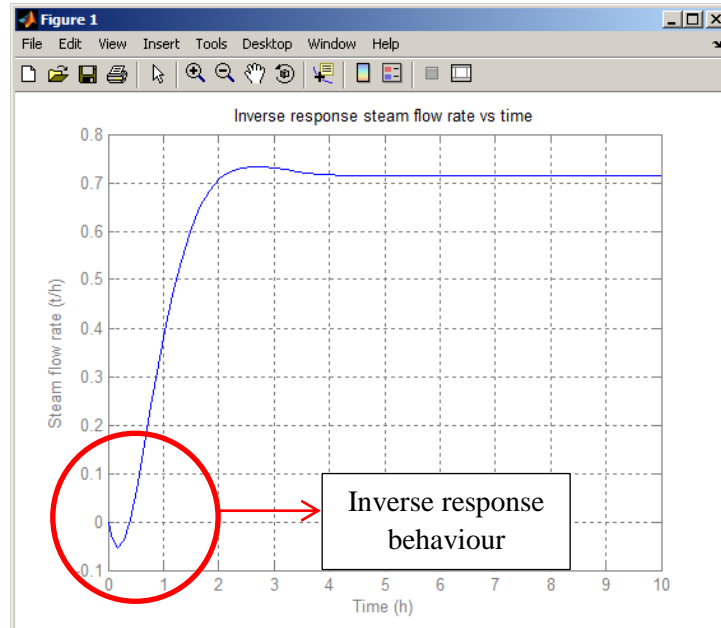


Figure 14: Inverse response process municipal incineration plant, Germany

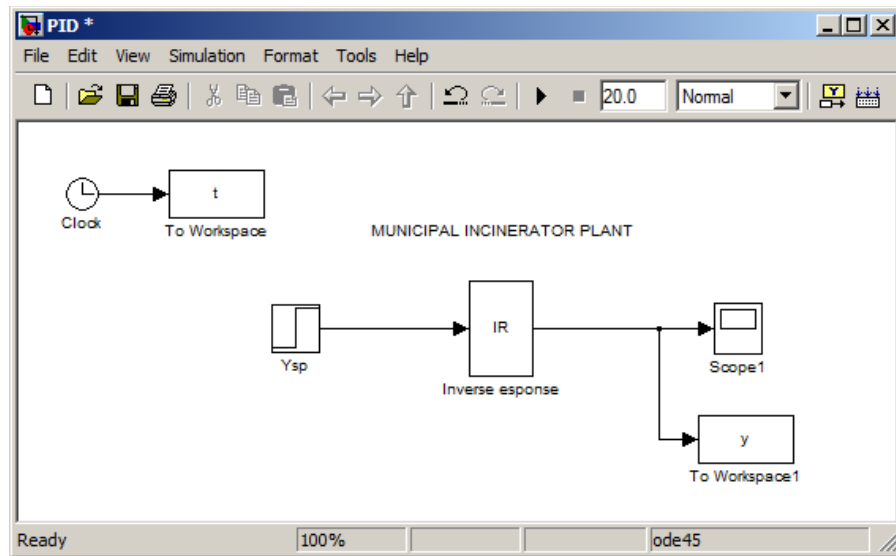


Figure 15: Model of the process

The first step in controlling the municipal incineration plant is to develop a plant model using the transfer function obtained. A simple model can be developed by using MATLAB Simulink software where the simulation can also be done by using this type of software. The inverse response system has been merging into a subsystem to simplify the model. Further detail of the inverse response and PID model can be seen in the appendix section.

3.3 Control of inverse response using PID controller with Ziegler-Nichols tuning method

Ziegler Nichols is a popular method for tuning proportional, proportional integral, and proportional integral derivative control system. It was first developed by John G. Ziegler and Nathaniel B. Nichols. This method has been widely known as one of the best tuning method for PID controller. The tuning parameter for Ziegler Nichols method can be determined both by simulation or manual calculation.

3.3.1 Procedure of tuning using Ziegler-Nichols method (MATLAB)

For experimental determination of K_{cu} and T_u using MATLAB Simulink,

1. The integral mode is removed by setting the integral time to its highest value for example gain integral = 99999. Otherwise, PID controller if the PID controller allows the switching off the integral mode, it is then switched off.
2. The derivative mode is also removed by setting the derivative time to its lowest value. Typically the value will be set to gain derivative = 0.
3. Once the integral and derivative mode has been set to the required value, the controller now become proportional controller only. The proportional gain is then set up to any value starting with 0.1 until obtaining an evenly oscillatory output graph. After each increase, the control loop was disturbed by introducing a small step change in set-point. The graph will be constantly observed in order to know the behavior and response of the controlled variable. The controlled variable should start oscillating as the gain is increased. When the amplitude of the oscillation remains approximately constant, the ultimate control gain has been reached. The value of K_{cu} is then recorded.
4. The period of the constant oscillation is also measured and recorded as T_u .

The procedure to obtain the value of K_{cu} and T_u is quite simple and requires a minimum upset to the process, just enough to be able to observe the behavior of the oscillation.

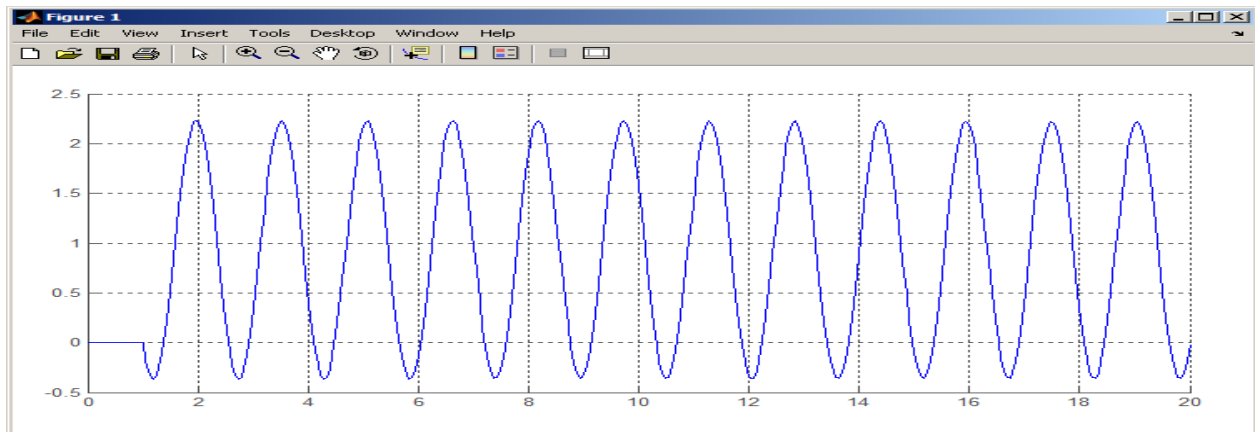


Figure 16: MATLAB Simulation to obtain K_{cu}

From simulation,

$$K_{cu} = 5.5$$

$$T_u = 2.34$$

4.2.2 Procedure of tuning using Ziegler-Nichols method (Manual)

$$G(s) = \frac{3}{3s+1} - \frac{0.5}{0.3s+1} \quad (17)$$

Simplified into:

$$G(s) = \frac{-0.6s+2.5}{(3s+1)(0.3s+1)} \quad (18)$$

Assume:

$$G_c = K_c \quad G_v = G_m = 1 \quad G_p = G(s) = \frac{-0.6s+2.5}{(3s+1)(0.3s+1)}$$

$$G_{OL}(s) = G_c G_p G_v G_m \quad (19)$$

$$G_{OL}(s) = \frac{(K_c)(-0.6s+1)(1)(1)}{(3s+1)(0.3s+1)} \quad (20)$$

$$G_{OL}(\omega j) = \frac{(K_c)(-0.6\omega j+1)(1)(1)}{(3\omega j+1)(0.3\omega j+1)} \quad (21)$$

$$G_{OL}(\omega j) = \frac{(K_c)(-0.6\omega j+1)}{(3\omega j+1)(0.3\omega j+1)} \quad (22)$$

$$\emptyset = \tan^{-1}(-0.6\omega/1) - \tan^{-1}(3\omega/1) - \tan^{-1}(0.3\omega/1) \quad (23)$$

$$\emptyset = \tan^{-1}(-0.6\omega) - \tan^{-1}(3\omega) - \tan^{-1}(0.3\omega) \quad (24)$$

$$\emptyset(\omega_c) = -\pi \quad (25)$$

$$-\pi = \tan^{-1}(-0.6\omega_c) - \tan^{-1}(3\omega_c) - \tan^{-1}(0.3\omega_c) \quad (26)$$

The value of ω_c can be obtained by substituting the equation into command window in MATLAB.

$$\omega_c = 2.687$$

$$|AR| = \frac{K_c(\sqrt{(-0.6 \omega)^2 + 1^2})}{(\sqrt{(3 \omega)^2 + 1^2})(\sqrt{(0.3 \omega)^2 + 1^2})} \quad (27)$$

When $AR = 1$, $\omega = \omega_c$ $K_c = K_{cu}$

$$|1| = \frac{K_{cu}(\sqrt{(-0.6 \omega_c)^2 + 1^2})}{(\sqrt{(3 \omega_c)^2 + 1^2})(\sqrt{(0.3 \omega_c)^2 + 1^2})} \quad (28)$$

Substitute the value of $\omega_c = 0.3745$ into the equation

$$|1| = \frac{K_{cu}(\sqrt{(-0.6 (2.687))^2 + 1^2})}{(\sqrt{(3 (2.687))^2 + 1^2})(\sqrt{(0.3 (2.687))^2 + 1^2})} \quad (29)$$

$$K_{cu} = 5.499$$

$$T_u = \frac{2\pi}{\omega_c} \quad (30)$$

Substitute the value of $\omega_c = 0.3745$ into the equation

$$T_u = \frac{2\pi}{2.687}$$

$$T_u = 2.338$$

Compare the manual calculation with experimental calculation

$$\begin{aligned} \text{Percentage error } (K_{cu}) &= ((\text{Theoretical value} - \text{Experimental value}) / \text{Theoretical value}) \times 100\% \\ &= (5.499 - 5.5) / 5.499 \times 100\% \\ &= \mathbf{-0.018\% \text{ error}} \end{aligned}$$

$$\begin{aligned} \text{Percentage error } (T_u) &= ((\text{Theoretical value} - \text{Experimental value}) / \text{Theoretical value}) \times 100\% \\ &= (2.338 - 2.34) / 2.338 \times 100\% \\ &= \mathbf{-0.086\% \text{ error}} \end{aligned}$$

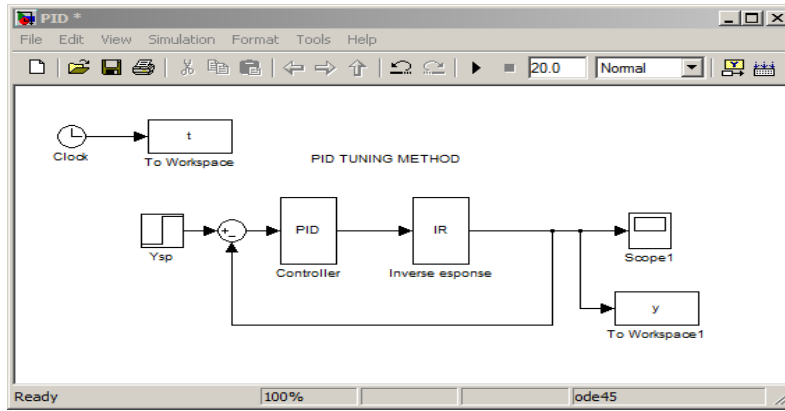


Figure 17: PID block diagram

After the tuning parameter has been set up, the values are inserted to PID controller that has been developed using MATLAB.

Zeigler-Nichols (ZN) controller setting:

Table 1: Ziegler-Nichols controller setting

	Controller parameters		
Controller	K_c	τ_I	τ_D
P	$\frac{K_{cu}}{2}$		
PI	$\frac{K_{cu}}{2.2}$	$\frac{T_u}{1.2}$	
PID	$\frac{K_{cu}}{1.7}$	$\frac{T_u}{2}$	$\frac{T_u}{8}$

Substitute the value of K_{cu} and T_u into the Ziegler-Nichols parameter:

Table 2: calculated value ZN

	Controller parameters		
Controller	K_c	τ_I	τ_D

P	2.7495		
PI	2.4996	1.9483	
PID	3.2347	1.1690	0.2923

3.4 Control of inverse response using PID controller with SIMC tuning method

3.4.1 Model approximation

The plant model can be approximated as a time delay:

$$(-T^{\text{inv}} s + 1) \approx e^{-T^{\text{inv}} s}$$

This is practical as an inverse response has a deteriorating effect on control which is similar compared to time delay, Skogestad and Postlethwaite (1996).

From the equation of inverse response derived before, $G(s) = \frac{-0.6s+2.5}{(3s+1)(0.32+1)}$

Numerator $\rightarrow (-0.6s + 2.5) = 2.5 (-0.24 s + 1) \approx e^{-0.24s}$

Where in this case, $\theta = 0.24$

So the model now become a second order equation plus time delay, $G(s) = \frac{2.5e^{-0.24s}}{(3s+1)(0.3s+1)} \quad (31)$

3.4.2 Derivation of SIMC-PID tuning rules

The derivation for SIMC PID tuning rules by Skogestad (2004), can be further seen in the appendix section. After derivation, the recommended SIMC-PID settings for second order time delay process are:

$$K_c = \frac{1}{k} \frac{\tau_1}{\tau_c + \theta} = \frac{1}{k'} \frac{1}{\tau_c + \theta} \quad \tau_I = \min \{ \tau_1, 4 (\tau_c + \theta) \} \quad \tau_D = \tau_2$$

(τ_c is a tuning parameter)

In order to obtain an output with good stability, robustness, and small input variation, a good trade off can be obtained by choosing τ_c to be equal to time delay. So, $\tau_c = \theta = 0.24$.

The equation can be further simplified to:

$$K_c = \frac{1}{k'} \frac{0.5}{\theta} \quad \tau_I = \min \{ \tau_1, 8\theta \} \quad \tau_D = \tau_2$$

By substituting values of τ_1 , τ_2 , K , τ_c , and θ , the SIMC-PID tuning setting become:

$$K_c = 2.5 \quad \tau_I = \min (3, 1.92) \quad \tau_D = 0.3$$

3.5 Control of inverse response using MPC

3.5.1 Prediction

The process model that is being used for this MPC method is the step response of the plant. At the beginning of the design, the author will conduct a step response to the plant and obtain the output. However, in this case, the disturbance is considered to be constant along the horizon. The prediction is obtained by first employing the step response model using equation below:

$$y(t) = \sum_{i=1}^{\infty} g_i \Delta u(t-i) \quad (32)$$

Thus, the predicted values along the horizon can be obtained by adding the plant model together with noise or disturbance:

$$\hat{y}(t+k|t) = \sum_{i=1}^{\infty} g_i \Delta u(t+k-i) + f(t+k) \quad (33)$$

Where, in this case, $f(t+k)$ is actually the free response of the system. Free response indicates the force or response that does not depend on the future control actions and is given by equation:

$$f(t+k) = y_m(t) + \sum_{i=1}^{\infty} (g_{k+1} - g_i) \Delta u(t-i) \quad (34)$$

After arranging the sequence, the prediction can be written as:

$$\hat{y} = Gu + f \quad (35)$$

3.5.2 Control algorithm

As been discussed before, the main aim of MPC is to bring the output to be as close as possible to the reference trajectory. Thus, the manipulated variables are selected to reduce a quadratic objective that can consider the minimization of future errors alone. After several derivations, the future control increments or corrective action can be obtained using formula:

$$u = (G^T G + \lambda I)^{-1} G^T (w - f) \quad (36)$$

From the equation, only the first element of vector u can be used and will be really sent to the plant. It is not advisable to include other vectors since in actual case, it is impossible to perfectly estimate the disturbance vector and thus precisely anticipate to unavoidable disturbance that can cause the output to diverge away from the predicted set point. Not only that, the set point also might be changed throughout the intervals.

3.6 Designing MPC using MATLAB Simulink toolbox

In order to come out with the best possible design for MPC using MATLAB Simulink tool box,

3.6.1 Analysing the effect of tuning parameter (weight) to MPC output

The simultaneous objective of an MPC controller is to minimize the weighted sum of adjustments made by the controller. In order to penalize any incremental change rather than cumulative value, the author will need to adjust the rate weight of the controller input. Hence, to obtain the most appropriate value for tuning parameter rate weight, several simulations need to be done to observe the effect of having high rate weight and low rate weight. The author will perform simulation step by step by first inserting a low value for rate weight and obtain the error from there. The steps will then be repeated for an increasing rate weight to make sure that the author can observe the trend of changing the rate weight.

3.6.2 Analysing the effect of prediction horizon (P) to MPC output

Prediction horizon sets the number of interval over which the output will be optimized. Prediction horizon is the range of every controller prediction made where it is expressed as an integer number of the future control intervals. Most designers prefer to choose the prediction horizon such that the controller performance is not sensitive to small adjustments in the control horizon. According to the rule of thumb for a stable process, prediction horizon should be chosen such that it is the same as control interval value. In order to observe the effect of prediction horizon, the author will undergo some tests by increasing the prediction horizon step by step.

3.6.3 Analysing the effect of control horizon (M) to MPC output

Control horizon sets the number of interval over which the output will be optimized. It is actually the number of moves computed for every manipulated variable. The effect of changing control horizon also will be monitored to enable the author to choose the best design for MPC method. For a Single Output Single Input (SISO) plant that has an inverse response, the plant optimization should focus mainly on the longer-term behaviour. Or else, the controller will diverge to a wrong direction than the intended set point. The procedure to analyse the

behaviour of control horizon is almost the same as prediction horizon. The only difference is, the author will change the control horizon while making the prediction horizon at constant value. The control horizon that will be set should be relatively small for example from 3 to 5 only.

3.7 Tuning MPC non-inverse response

Other than simulating MPC tuning for inverse response, the author would like to extend the research on the non-inverse process as well. By using the same municipal incineration plant model, the author will eliminate the effect of inverse response and use the direct response of $G = \frac{3}{3s+1}$ only. Figure below shows the block diagram of direct response:

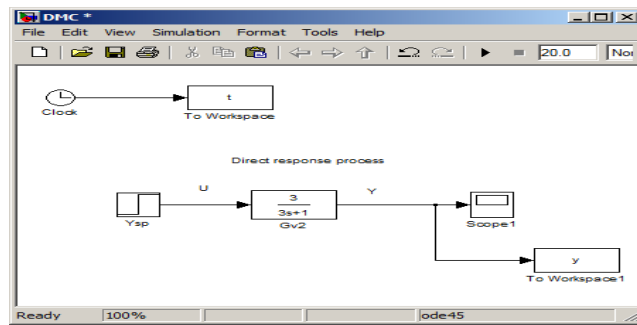


Figure 18: Direct response process

For direct response, the author will again, use MPC tool in MATLAB Simulink to control the process. Nevertheless, proper tuning should be done in order to obtain an optimum output with a small amount of error. Same steps as tuning inverse response process are conducted and errors will then be calculated and compared to the inverse response process.

3.8 Software

- MATLAB Simulink 7.1

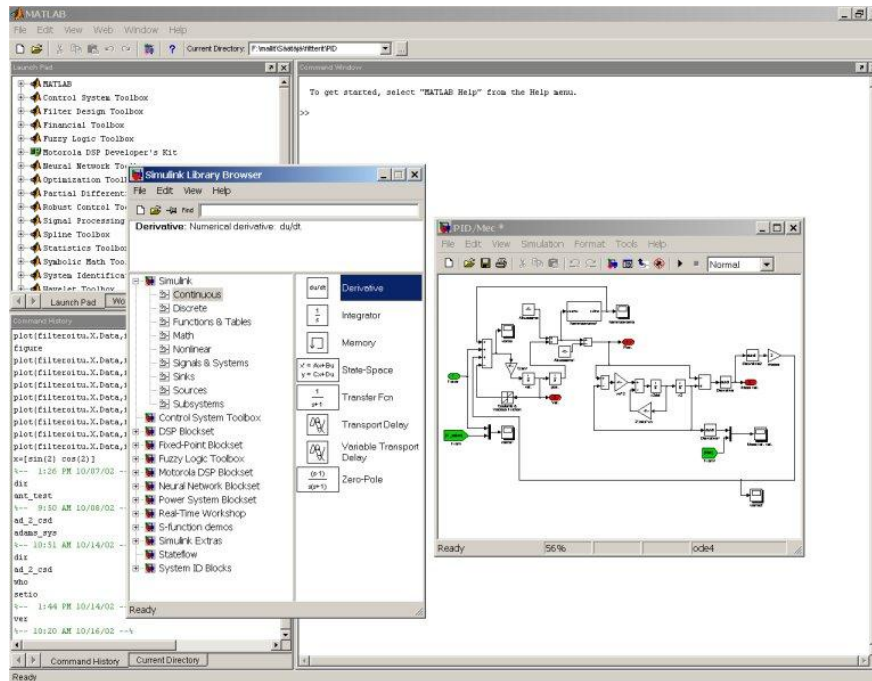


Figure 19: MATLAB Simulink

For designing MPC using readily available tools in MATLAB, the author will be using a a toolbox or command function ‘mpctool’ in MATLAB Simulink as a tool to explore and control the inverse response process that occurs in industry. Model Predictive Control Toolbox in MATLAB can assist to runs tools for analytically analysing, designing, and tuning model predictive controllers. It is possible to simply design and simulate model predictive controllers using functions in MATLAB or blocks in Simulink. The author can set and modify the predictive model, control and prediction horizons, input and output constraints, and weights. Other than that, the toolbox makes it convenient to diagnose issues that could lead to run-time failures and provides advice on changing weights and constraints to improve performance and robustness. By running different scenarios in linear and nonlinear simulations, author can evaluate controller performance by adjusting controller performance as it runs by tuning weights and varying constraints. This software is also handy for rapid prototyping and embedded system design, the

toolbox supports C-code generation. MATLAB Simulink does not only provide a model for controller, it also helps the author to develop her own controller which suits to the problem of inverse response. The author will then use MATLAB to write coding and evaluate the performance of the designed controller.

3.9 Key Milestone

Final Year Project 1

No	Detail/week	1	2	3	4	5	6	7	Mid-Semester break	8	9	10	11	12	13	14
1	First meeting with coordinator															
2	Preliminary research work															
3	Submission of Extended Proposal Defence															
4	Proposal Defence															
5	Project work continues															
6	Submission of Interim Draft Report															
7	Submission of Interim Report															

Final Year Project 2

No	Detail/week	1	2	3	4	5	6	7	Mid-Semester break	8	9	10	11	12	13	14	15
1	Identify case study	20/9															
2	Develop process model		24/9														
3	Develop control system – Simple feedback with PID Ziegler Nichols tuning		25/9														
4	Develop control system – Simple feedback with SIMC tuning			1/10													
5	Identify MPC method				8/10												
6	Develop control system -MPC				9/10												
7	Submission of progress report									5/11							
8	Pre-Sedex												26/11				
9	Submission of draft report													3/12			
10	Submission of dissertation (soft bound)														10/12		
11	Submission of technical paper														10/12		
12	Oral Presentation															19/12	
13	Submission of project dissertation (hard bound)																11/1

CHAPTER 4

RESULT AND DISCUSSIONS

4.1 Evaluating performance of PID tuning

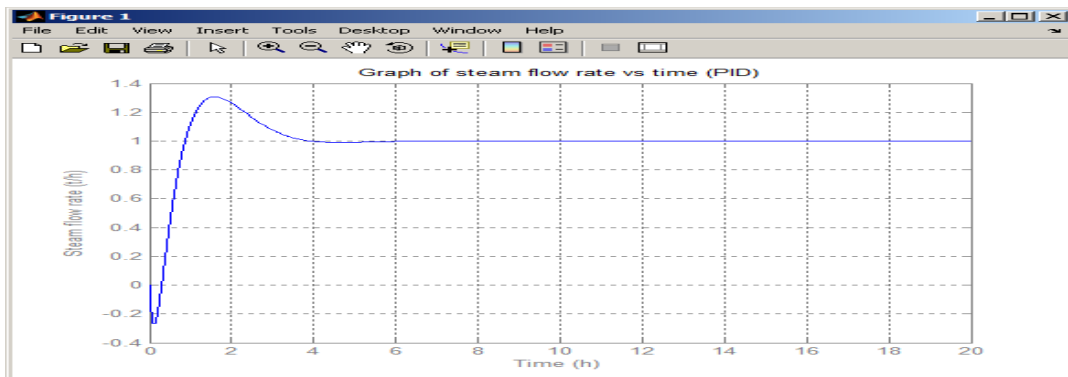


Figure 20: Graph of output vs time (PID)

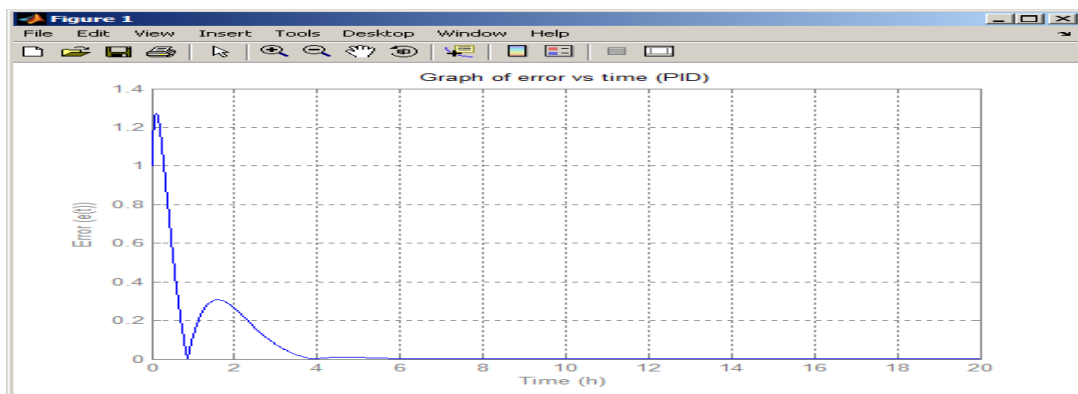


Figure 21: Graph of error vs time (PID)

4.2 Evaluating performance of SIMC tuning

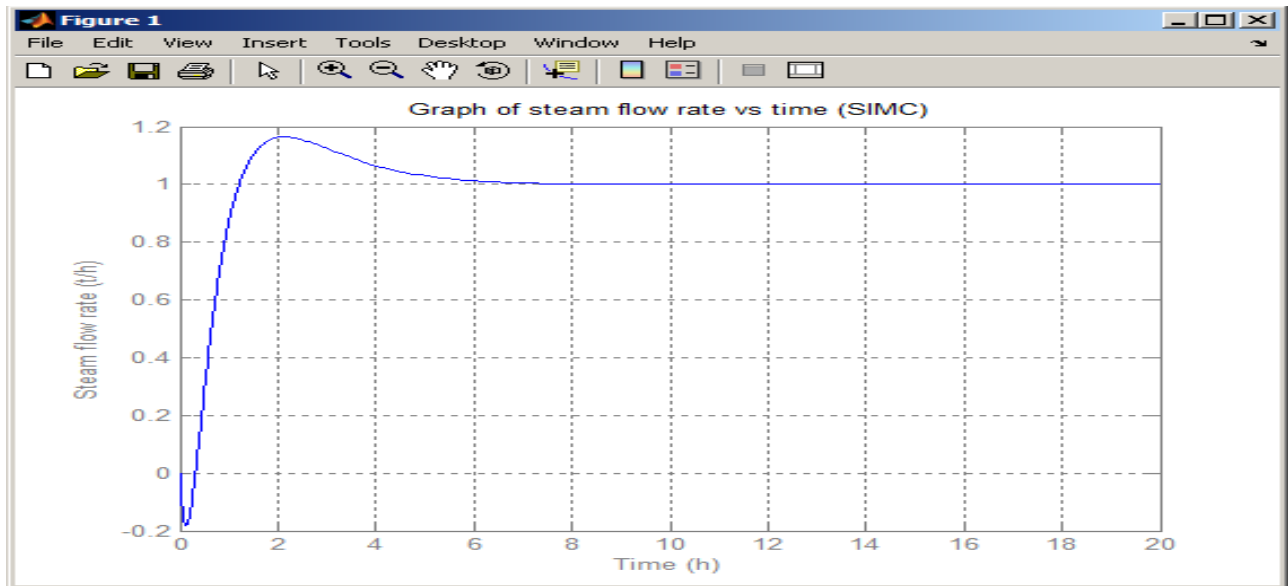


Figure 22: Graph of output vs time (SIMC)

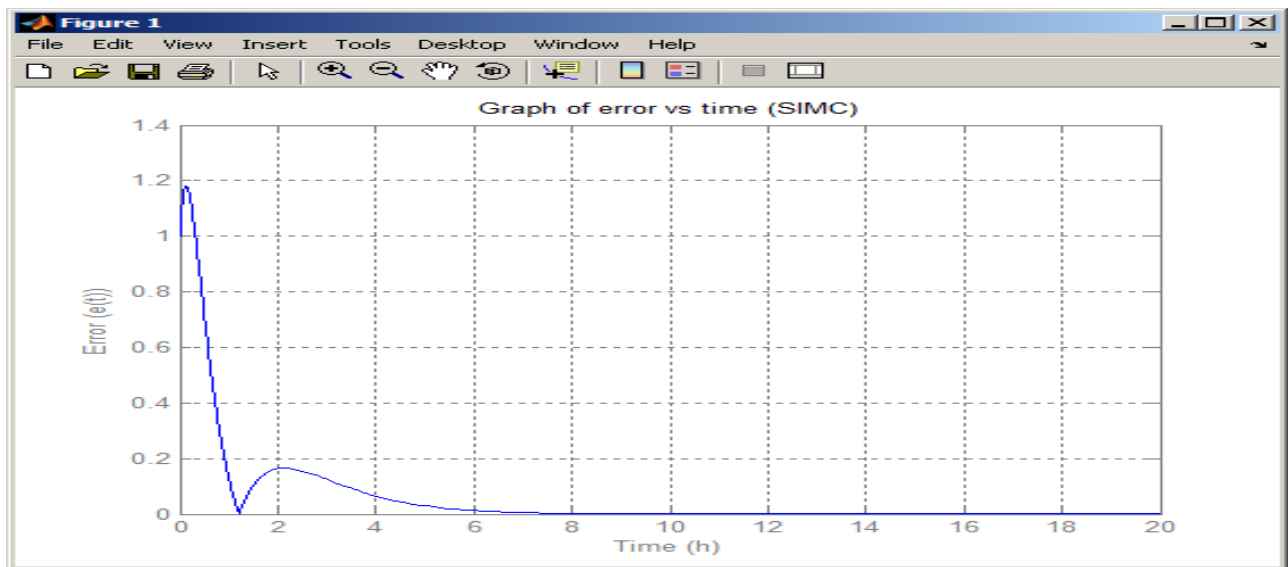


Figure 23: Graph of error vs time (SIMC)

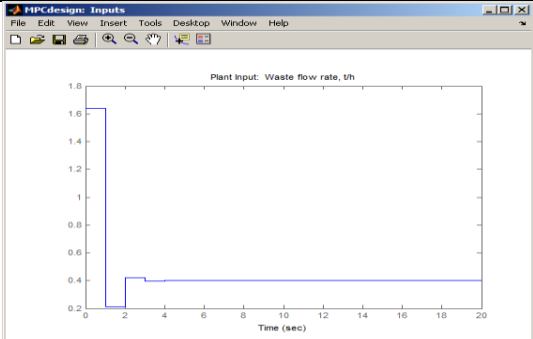
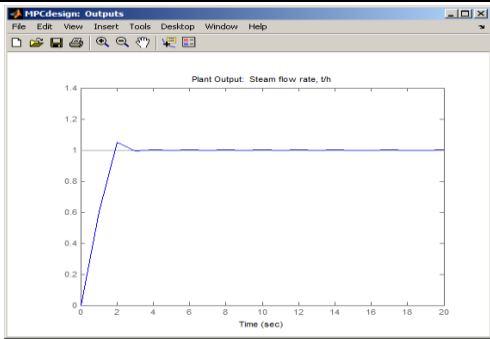
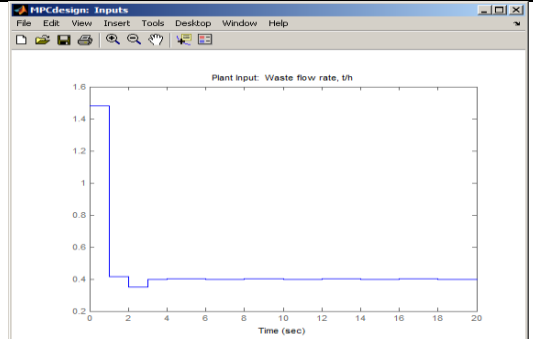
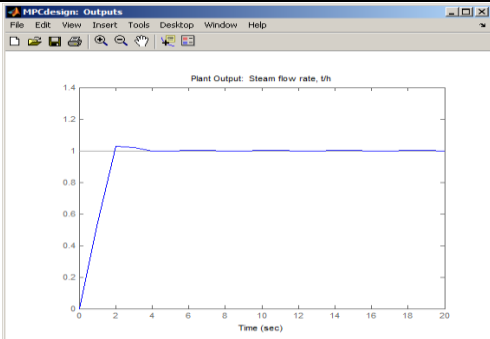
4.3 Evaluating tuning parameter for MPC

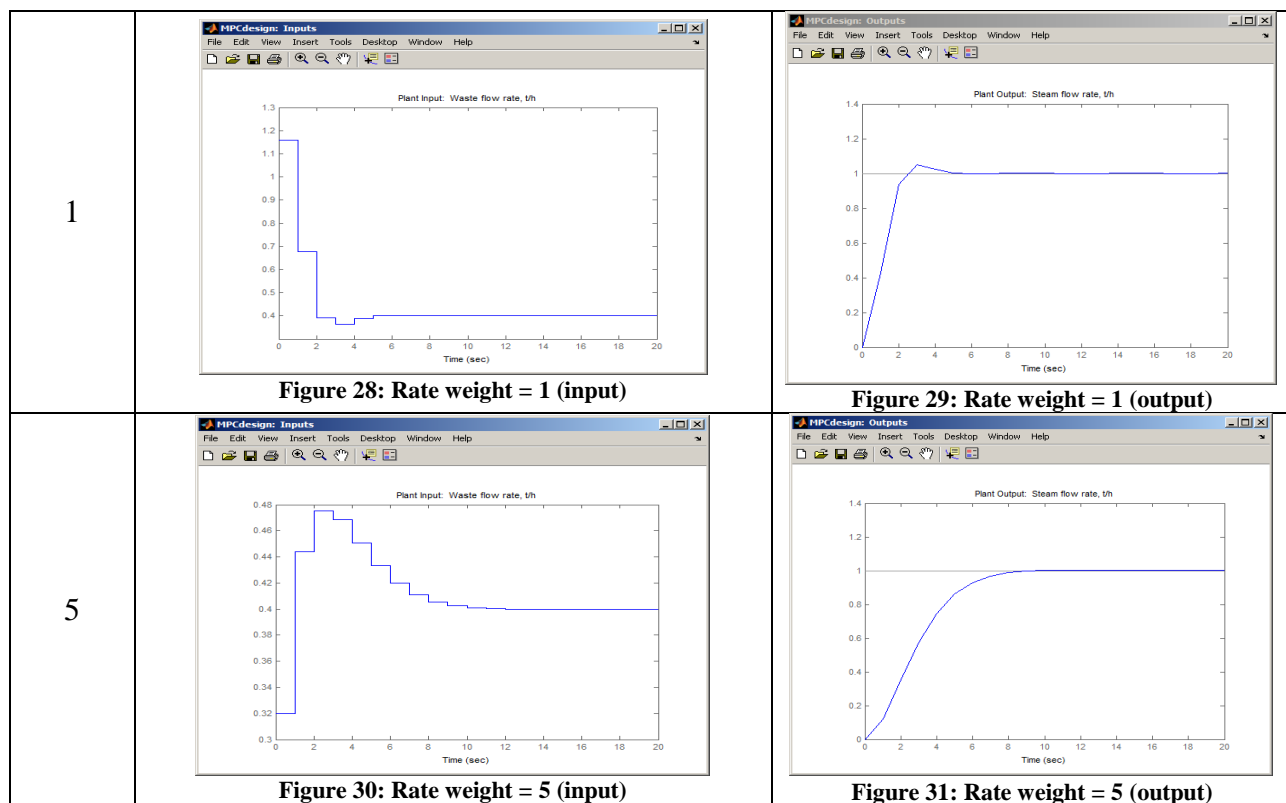
4.1.1 Rate Weight

Table 3: Rate weight analysis for output

Rate weight \ Error	0.1	0.5	1	5
IAE	0.9508	1.0062	1.2168	2.9669
ISE	0.6598	0.7078	0.8364	1.9652
ITAE	0.5109	0.5836	0.9763	6.0070

Rate weight

Rate Weight	Input	Output
0.1	 <p>Figure 24: Rate weight = 0.1 (input)</p>	 <p>Figure 25: Rate weight = 0.1 (output)</p>
0.5	 <p>Figure 26: Rate weight = 0.5 (input)</p>	 <p>Figure 27: Rate weight = 0.5 (output)</p>



Rate weight analysis of the valve adjustment

Table 4: Input adjustment analysis

0.1		0.5		1		5	
1.638	-	1.481	-	1.1577	-	0.3196	-
1.638	0	1.481	0	1.1577	0	0.3196	0
0.213	1.425	0.413	1.068	0.6786	0.4791	0.4439	0.1243
0.213	0	0.413	0	0.6786	0	0.4439	0
0.419	0.206	0.351	0.0621	0.3912	0.2874	0.4752	0.0313
0.419	0	0.351	0	0.3912	0	0.4752	0
0.398	0.021	0.399	0.0482	0.363	0.0282	0.4686	0.0066
0.398	0	0.399	0	0.363	0	0.4686	0
0.4	0.002	0.402	0.0028	0.3898	0.0268	0.4508	0.0178
0.4	0	0.402	0	0.3898	0	0.4508	0
0.4	0	0.400	0.0022	0.4015	0.0117	0.4334	0.0174
0.4	0	0.400	0	0.4015	0	0.4334	0

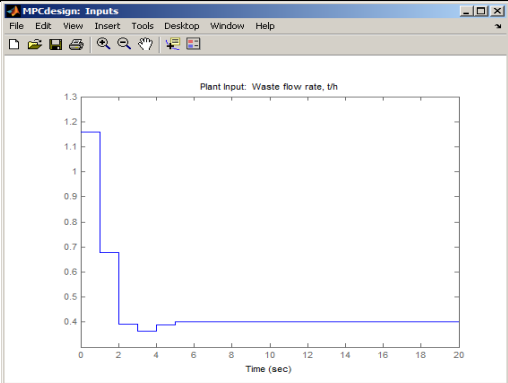
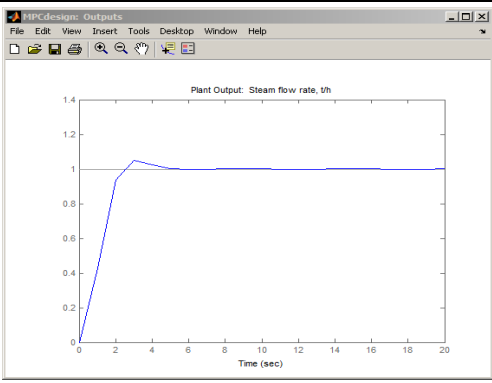
0.4	0	0.400	0.0001	0.4017	0.0002	0.4201	0.0133
0.4	0	0.400	0	0.4017	0	0.4201	0
0.4	0	0.400	0.0001	0.4003	0.0014	0.4111	0.009
0.4	0	0.400	0	0.4003	0	0.4111	0
0.4	0	0.400	0	0.3999	0.0004	0.4056	0.0055
0.4	0	0.400	0	0.3999	0	0.4056	0
0.4	0	0.400	0	0.3999	0	0.4025	0.0031
0.4	0	0.400	0	0.3999	0	0.4025	0
0.4	0	0.400	0	0.4	0.0001	0.4009	0.0016
0.4	0	0.400	0	0.4	0	0.4009	0
0.4	0	0.400	0	0.4	0	0.4002	0.0007
0.4	0	0.400	0	0.4	0	0.4002	0
0.4	0	0.400	0	0.4	0	0.3999	0.0003
0.4	0	0.400	0	0.4	0	0.3999	0
0.4	0	0.400	0	0.4	0	0.3998	1E-04
0.4	0	0.400	0	0.4	0	0.3998	0
0.4	0	0.400	0	0.4	0	0.3998	0
0.4	0	0.400	0	0.4	0	0.3998	0
0.4	0	0.400	0	0.4	0	0.3999	1E-04
0.4	0	0.400	0	0.4	0	0.3999	0
0.4	0	0.400	0	0.4	0	0.3999	0
0.4	0	0.400	0	0.4	0	0.3999	0
0.4	0	0.400	0	0.4	0	0.4	0.0001
0.4	0	0.400	0	0.4	0	0.4	0
0.4	0	0.400	0	0.4	0	0.4	0
0.4	0	0.400	0	0.4	0	0.4	0
0.4	0	0.400	0	0.4	0	0.4	0
0.4	0	0.400	0	0.4	0	0.4	0
0.4	0	0.400	0	0.4	0	0.4	0
Sum	1.654	Sum	1.1835	Sum	0.8353	Sum	0.2312

Based from result obtained, it can be concluded that increasing the weight will forces the controller to make smaller and more cautious adjustments can be made. Table above indicates that increasing a small amount of rate weight from 0.1 to 5 decreases the move sizes significantly, particularly the initial move. Setting the rate weight to a much smaller value such as 0.1 yields a faster approach to the set

point with a very small amount of overshoot. However, the initial adjustment will be around six times larger than what is needed to achieve the new steady state. In some application, this case will be unacceptable as it can cause damage to the valve. In order to obtain a smoother output, the rate weight can be adjusted to a slightly higher value. Still, the output error that is produced will increase even though the valve adjustment is made smoothly. The higher the rate weight, the smoother the adjustment of the valve and output will be. Conversely, the deviation of the output to the set point also increases since the amount of overshoot is much higher and time needed for the output to move to the set point is much longer than using small rate weight. Hence, from the analysis, the most appropriate rate weight to be used is 1 as the error is not too high and at the same time the valve adjustment is not too abrupt.

4.1.2 Prediction horizon

Prediction horizon

Prediction horizon	Input	Output
5	 <p>Figure 32: Prediction horizon = 5 (input)</p>	 <p>Figure 33: Prediction horizon = 5 (output)</p>

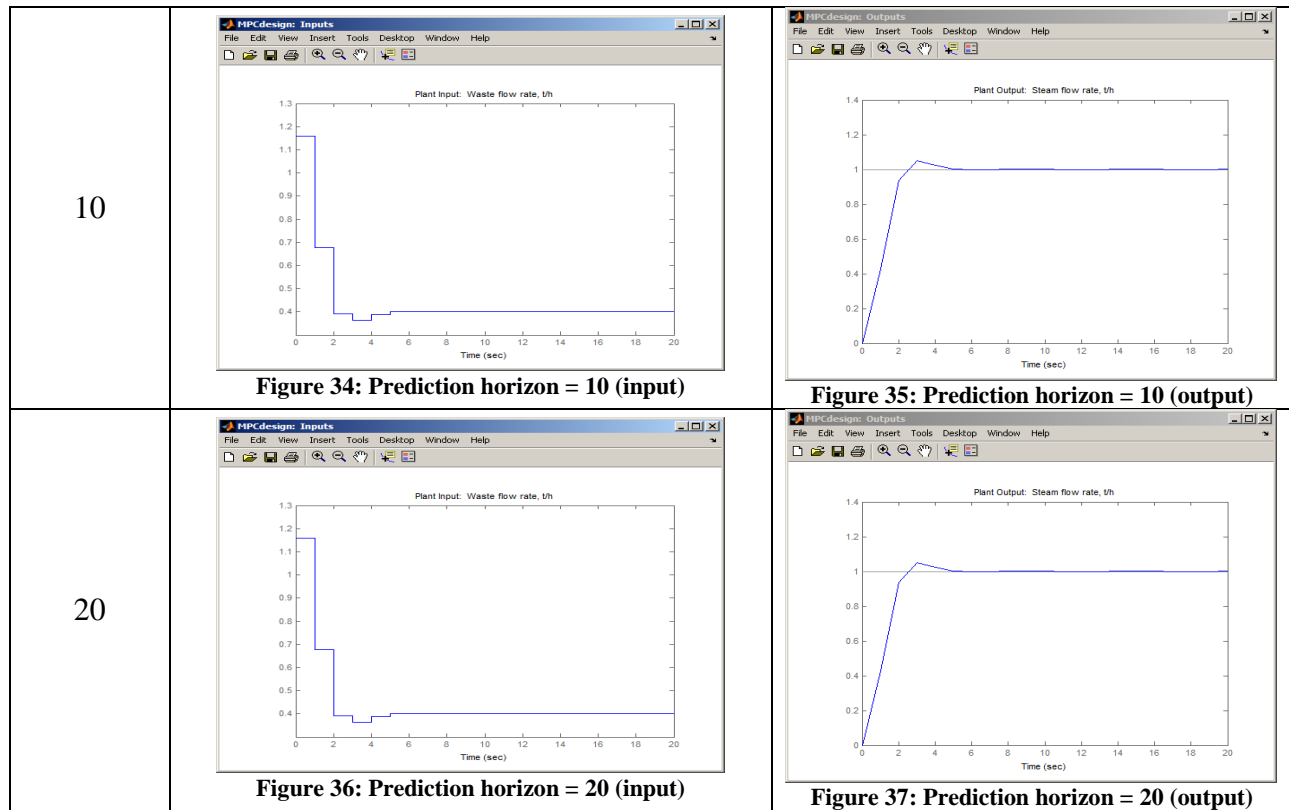


Table 5: Prediction horizon analysis for output

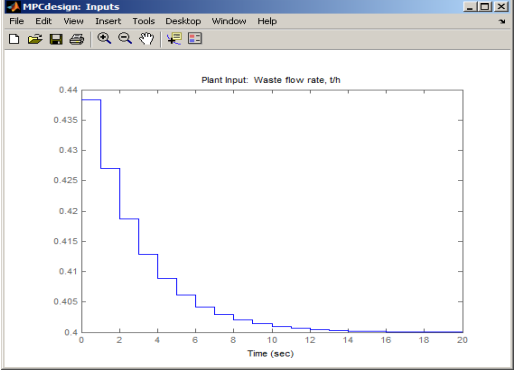
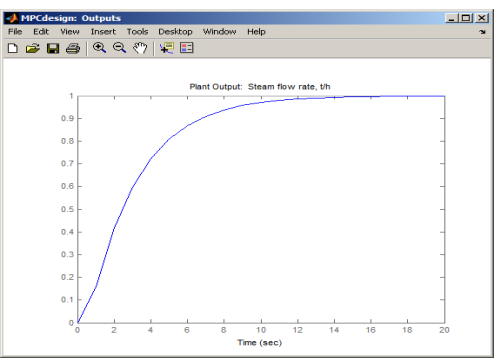
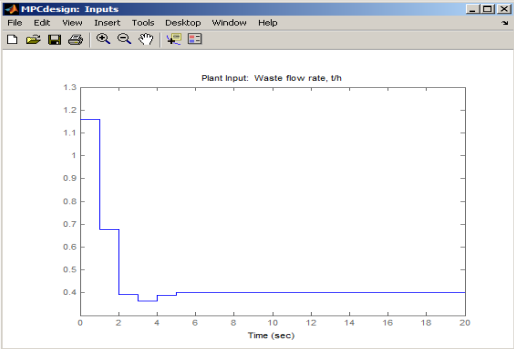
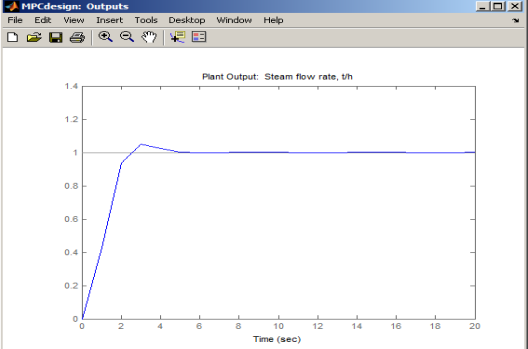
Prediction horizon		5	10	20
Error				
IAE		1.3181	1.2488	1.2168
ISE		0.8888	0.8519	0.8364
ITAE		1.1985	1.0480	0.9763

According to the rules of thumb, the value of the prediction horizon should be less than or equal to the control interval. Since the control interval that has been chosen in this simulation is 20, the value of prediction horizon should lie between 0 and 20. Based from the result obtained, it can be concluded that when the prediction horizon is equal to the control interval, the error produced is lesser than using low prediction horizon. Although the change in prediction horizon does not

affect much to the error, suitable value still needs to be chosen to represent the MPC. Hence, prediction horizon of 20 is chosen as the best value for this plant model.

4.1.3 Control horizon

Control horizon

Control horizon	Input	Output
1	 <p>Figure 38: Control horizon = 1 (input)</p>	 <p>Figure 39: Control horizon = 1 (output)</p>
2	 <p>Figure 40: Control horizon = 2 (input)</p>	 <p>Figure 41: Control horizon = 2 (output)</p>

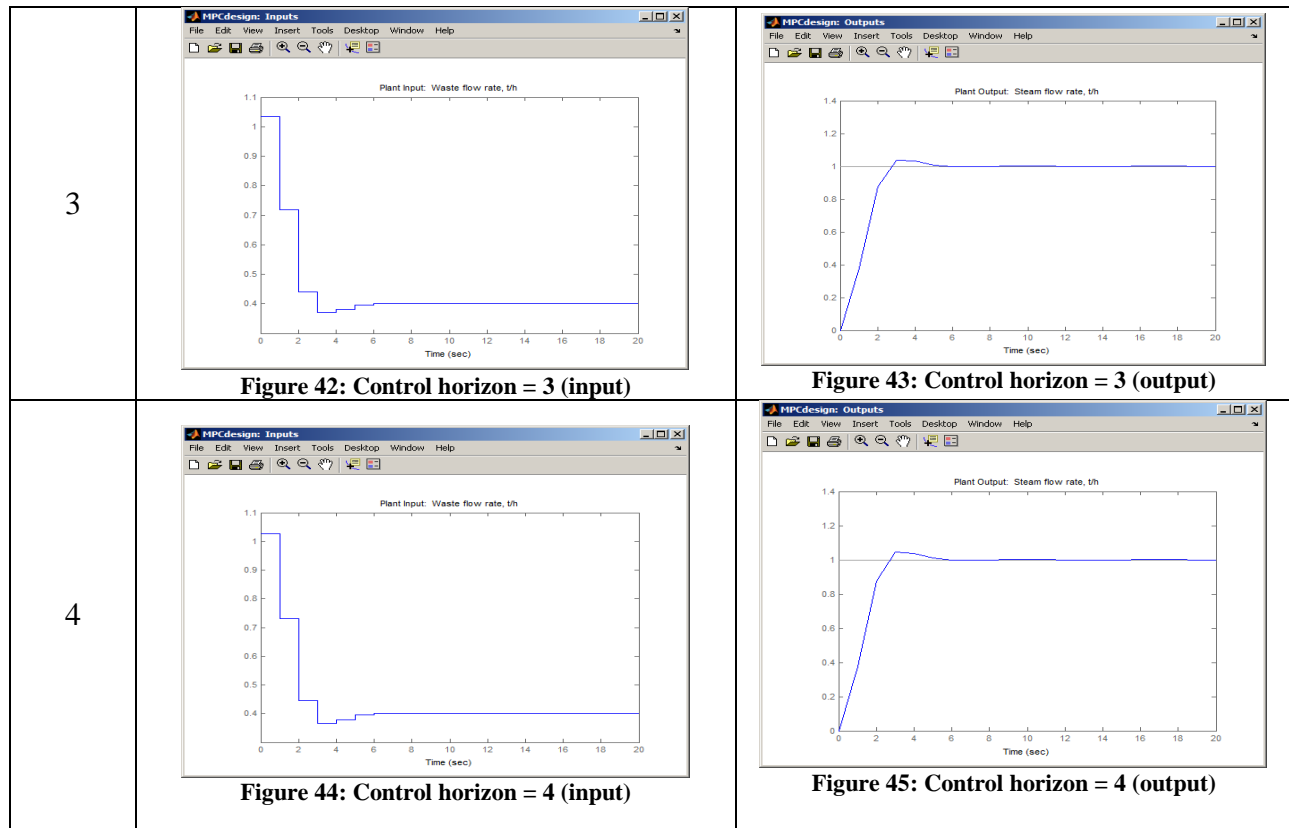


Table 6: Control horizon analysis for output

Control horizon \ Error	1	2	3	4
IAE	3.2109	1.2168	1.3265	1.3429
ISE	1.8506	0.8364	0.9010	0.9058
ITAE	8.6906	0.9763	1.1846	1.2399

By referring to the data above, it can be seen that the lower the value of control horizon, the lesser the amount of error can be found. It can be concluded that the experimental or simulation test is the same as what is said according to the rules of thumb where the most appropriate value of control prediction should lie between 2 to 5. The author has tried to extend the simulation by further lowering down the

control prediction to 1. Although the input adjustment is very smooth and the output also is very smooth, the amount of error is rather big compared to other control prediction. Control horizon 2 is the most suitable value to be chosen as it produces the least amount of error compared to other values.

4.4 Evaluating performance of MPC

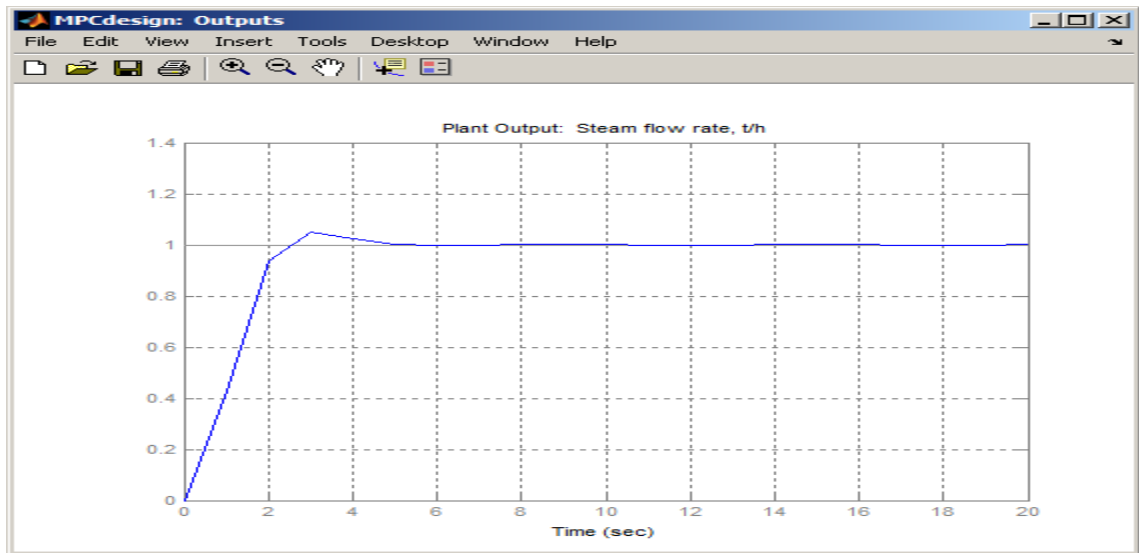


Figure 46: Graph of output vs time (MPC)

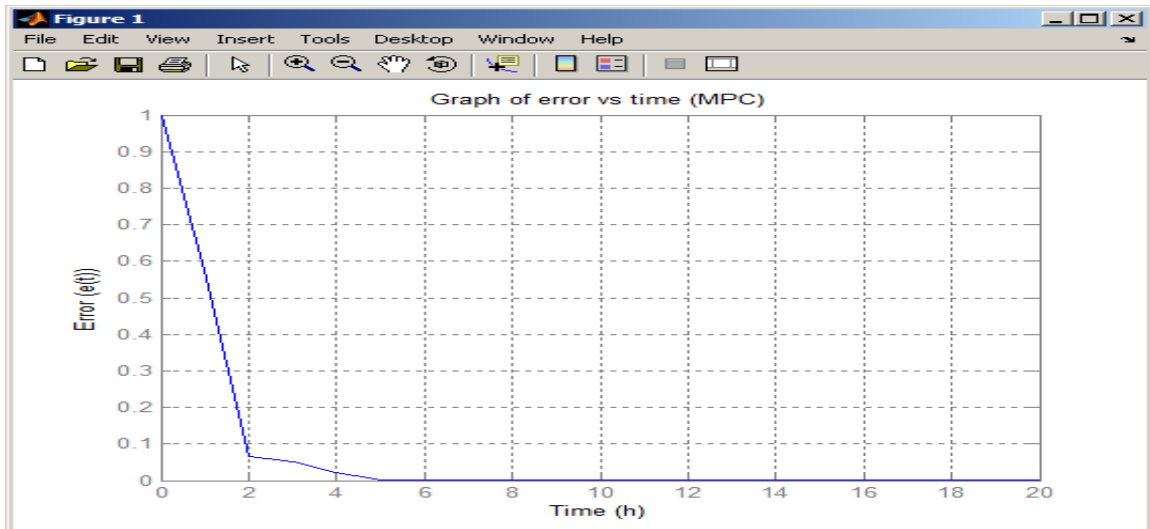
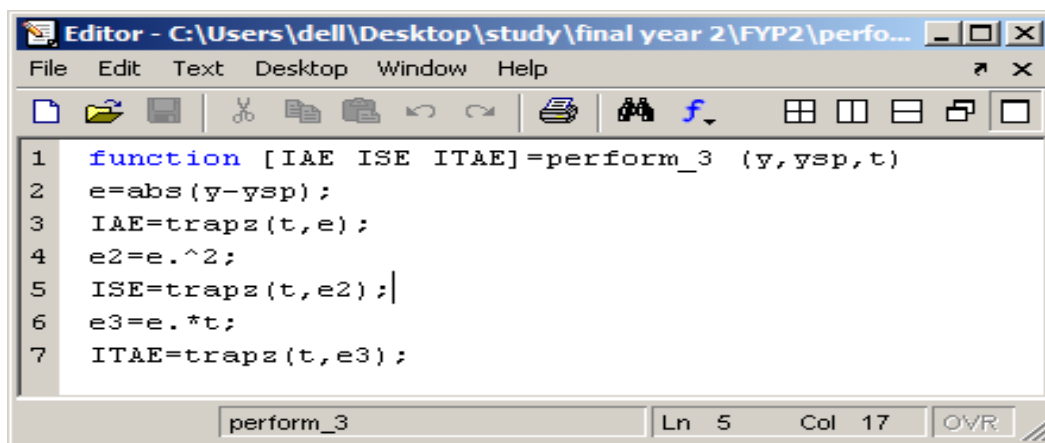


Figure 47: Graph of error vs time (MPC)

In order achieve the best output performance together with smooth input manipulation, proper tuning should be chosen for configuration of MPC. Based from the simulation tests done before, it can be concluded that rate weight of 1, prediction horizon of 20, and control horizon of 2 produce the least amount of error while having smooth adjustment for the valve.

4.5 Error calculation of the designed controllers

The performance of the designed controllers can be compared and evaluated by using these MATLAB coding that has been developed by the author herself.

A screenshot of a MATLAB Editor window. The title bar reads "Editor - C:\Users\dell\Desktop\study\final year 2\FYP2\perfo...". The menu bar includes "File", "Edit", "Text", "Desktop", "Window", and "Help". The toolbar contains icons for file operations (new, open, save, print) and editing (undo, redo, cut, copy, paste). The main text area contains the following MATLAB code:

```
1 function [IAE ISE ITAE]=perform_3 (y,ysp,t)
2 e=abs(y-ysp);
3 IAE=trapz(t,e);
4 e2=e.^2;
5 ISE=trapz(t,e2);
6 e3=e.*t;
7 ITAE=trapz(t,e3);
```

The status bar at the bottom shows "perform_3", "Ln 5", "Col 17", and "OVR".

Figure 48: m-coding for performance analysis

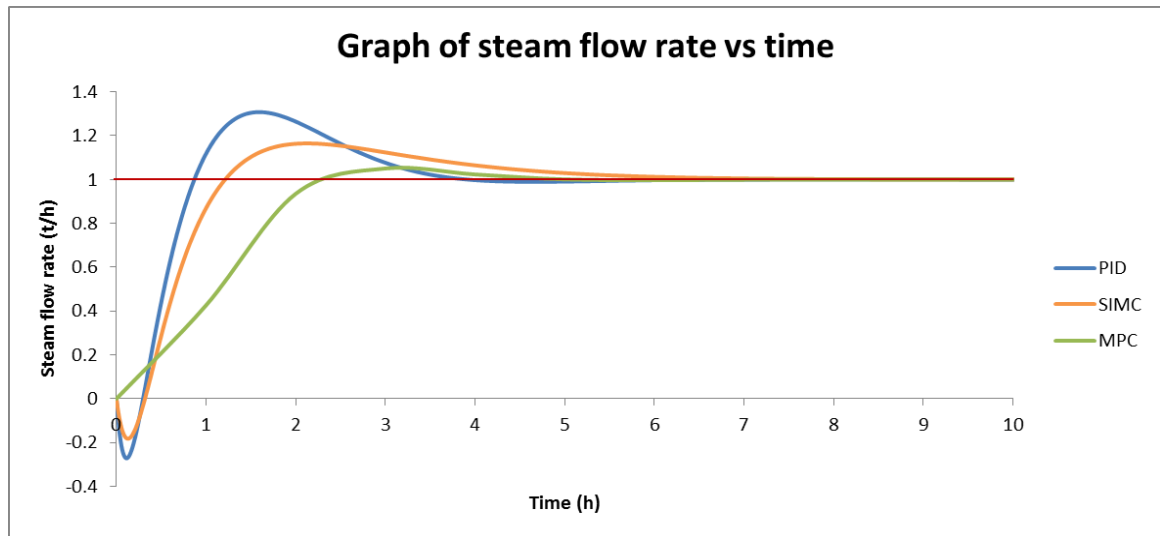


Figure 49: Overall performance

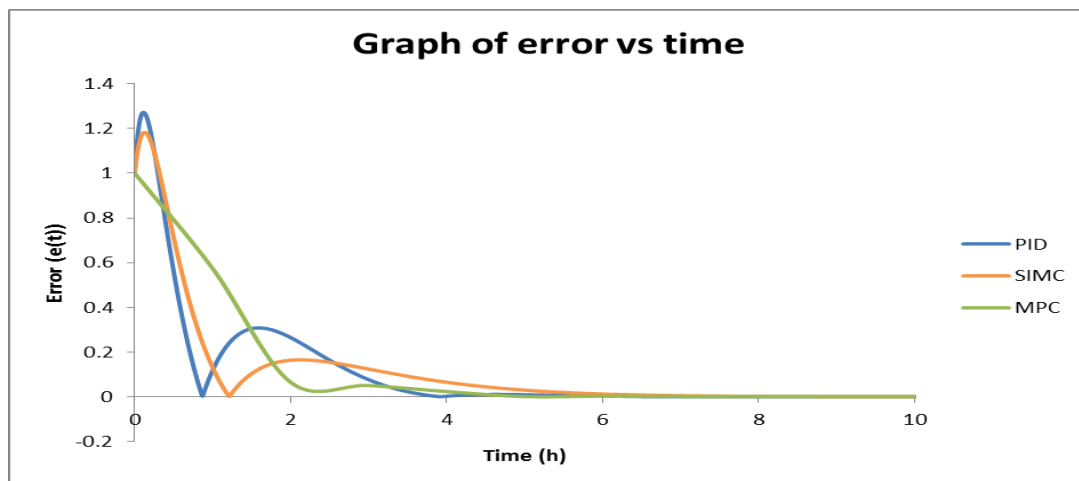


Figure 50: Overall error

Set point change (servo problem)

Table 7: Performance evaluation

Error	PID	SIMC	MPC
IAE	1.0849	1.1272	1.2168
ISE	0.6775	0.6695	0.8364
ITAE	1.1624	1.5095	0.9763

By comparing the Integral Absolute Error (IAE), it can be seen that MPC produce the largest error followed by SIMC and PID controller. As mentioned before, IAE represents the overall error that is measured during the determination of output's performance. It is the combination of time error together with overshoot in the output. When the amount of IAE is high, it indicates that the overall performance of MPC controller is not as good as PID and SIMC. Hence, by considering the overall performance, it can be concluded that PID will be the best controller to be used in controlling an inverse response process. However, in some cases, the manufacturer does not take the overall error critically. They may want to have a relatively small amount of overshoot and tolerate small amount of time delay before the output move to the set point. If this is the case, Integral Squared Error (ISE) is the best way to monitor amount of overshoot in the output. Among the three designed controllers, it is favourable to choose SIMC tuning compared to PID and MPC as SIMC has the least ISE error. This indicates that SIMC can reduce the amount of overshoot better than the former two. Some process in industries requires a fast response while at the same time can tolerate overshoot. In this circumstance, Integral Time Absolute Error (ITAE) can be used to monitor the output performance. Between the three controllers, MPC has shown the fastest response where the output takes just a short time to reach the set point. The error indicates is very small than using PID or SIMC tuning. Hence, if time is a critical criterion for the output, MPC will be the best solution among the designed controllers.

4.6 MPC tuning for non-inverse response

4.6.1 Rate weight

Table 8: Rate weight analysis for direct response

Error \ Rate Weight	0.1	0.5	1	5
IAE	0.5036	0.7861	1.2229	3.2828
ISE	0.5000	0.5536	0.7788	1.9678
ITAE	0.0046	0.3917	1.1303	8.3248

Table 9: Input adjustment analysis for direct response

0.1		0.5		1		5	
1.1729		0.9069		0.5826		0.1964	
1.1729	0	0.9069	0	0.5826	0	0.1964	0
0.3367	0.8362	0.5502	0.3567	0.5808	0.0018	0.2916	0.0952
0.3367	0	0.5502	0	0.5808	0	0.2916	0
0.3325	0.0042	0.3493	0.2009	0.4578	0.123	0.3336	0.042
0.3325	0	0.3493	0	0.4578	0	0.3336	0
0.3333	0.0008	0.318	0.0313	0.3704	0.0874	0.349	0.0154
0.3333	0	0.318	0	0.3704	0	0.349	0
0.3333	0	0.3269	0.0089	0.3338	0.0366	0.3521	0.0031
0.3333	0	0.3269	0	0.3338	0	0.3521	0
0.3333	0	0.3327	0.0058	0.3259	0.0079	0.3501	0.002
0.3333	0	0.3327	0	0.3259	0	0.3501	0
0.3333	0	0.3337	0.001	0.3279	0.002	0.3465	0.0036
0.3333	0	0.3337	0	0.3279	0	0.3465	0
0.3333	0	0.3335	0.0002	0.331	0.0031	0.343	0.0035
0.3333	0	0.3335	0	0.331	0	0.343	0
0.3333	0	0.3334	0.0001	0.3328	0.0018	0.3401	0.0029
0.3333	0	0.3334	0	0.3328	0	0.3401	0
0.3333	0	0.3333	1E-04	0.3334	0.0006	0.3379	0.0022
0.3333	0	0.3333	0	0.3334	0	0.3379	0
0.3333	0	0.3333	0	0.3335	0.0001	0.3363	0.0016

0.3333	0	0.3333	0	0.3335	0	0.3363	0
0.3333	0	0.3333	0	0.3334	0.0001	0.3353	0.001
0.3333	0	0.3333	0	0.3334	0	0.3353	0
0.3333	0	0.3333	0	0.3334	0	0.3345	0.0008
0.3333	0	0.3333	0	0.3334	0	0.3345	0
0.3333	0	0.3333	0	0.3333	1E-04	0.3341	0.0004
0.3333	0	0.3333	0	0.3333	0	0.3341	0
0.3333	0	0.3333	0	0.3333	0	0.3338	0.0003
0.3333	0	0.3333	0	0.3333	0	0.3338	0
0.3333	0	0.3333	0	0.3333	0	0.3336	0.0002
0.3333	0	0.3333	0	0.3333	0	0.3336	0
0.3333	0	0.3333	0	0.3333	0	0.3335	1E-04
0.3333	0	0.3333	0	0.3333	0	0.3335	0
0.3333	0	0.3333	0	0.3333	0	0.3334	0.0001
0.3333	0	0.3333	0	0.3333	0	0.3334	0
0.3333	0	0.3333	0	0.3333	0	0.3334	0
0.3333	0	0.3333	0	0.3333	0	0.3334	0
0.3333	0	0.3333	0	0.3333	0	0.3334	0
0.3333	0	0.3333	0	0.3333	0	0.3334	0
0.3333	0	0.3333	0	0.3333	0	0.3333	1E-04
Sum	0.8412	Sum	0.605	Sum	0.2645	Sum	0.1745

4.6.2 Prediction horizon

Table 10: Prediction horizon analysis for direct response

Prediction horizon Error	5	10	20
IAE	1.2272	1.1740	1.1426
ISE	0.7809	0.7481	0.7255
ITAE	1.1232	1.0367	0.9915

4.6.3 Control horizon

Table 11: Control horizon analysis for direct response

Control Horizon Error	1	2	3	4
IAE	2.7346	1.1426	1.1554	1.1918
ISE	1.4157	0.7255	0.7360	0.7612
ITAE	7.1865	0.9915	1.0039	1.0647

The result of simulation above indicates that the way of tuning MPC for inverse response and direct response is almost the same. For the direct response however, the author decided to choose rate weight of 2 as this value produce the smoothest valve adjustment while maintaining less amount of error. Same as the analysis for inverse response before, the most suitable value for prediction horizon must be equal to the control interval which is 20. The control horizon chosen is 2 since it produces the least error compared to other values. Figure below shows the output and input response after tuning of MPC.

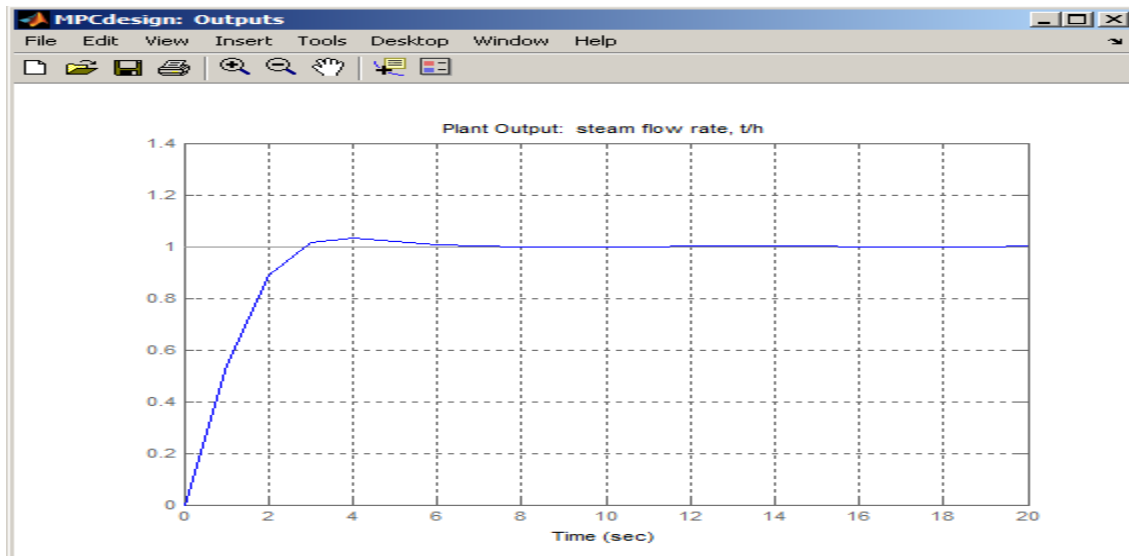


Figure 51: Graph of output vs time direct response (MPC)

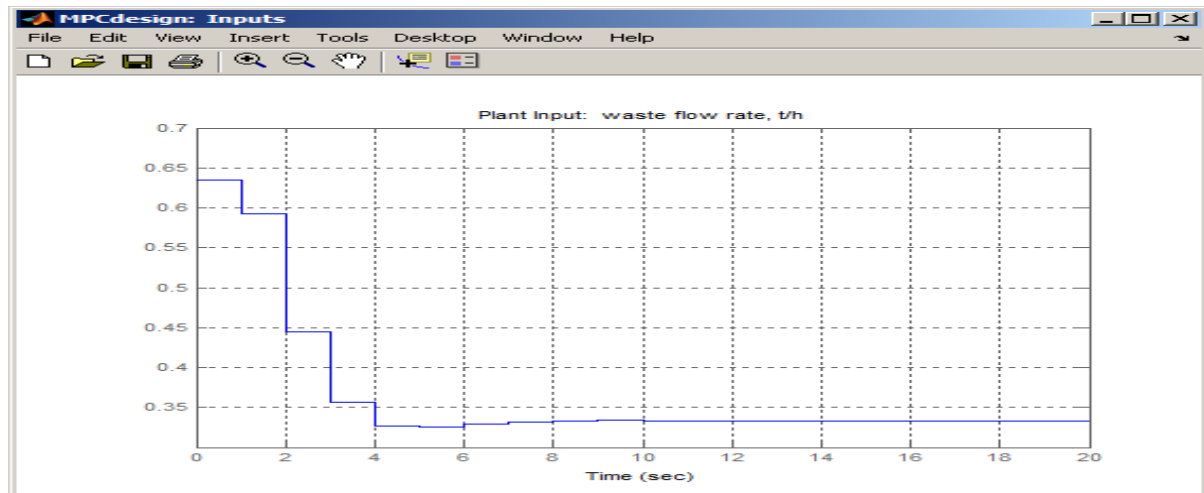


Figure 52: Graph of input vs time direct response (MPC)

CHAPTER 5

CONCLUSION

5.1 Conclusion and recommendation

Model Predictive Control or MPC has been proven to produce a fast response for output performance for an inverse response process. Not only that it is suitable for single input single output (SISO) process, MPC also is suitable to measure and take control action for the multiple inputs multiple outputs (MIMO) that affect the performance of the process. Besides providing an astonishing result, MPC possess many attributes which makes it a successful approach to industrial control design especially for inverse response process. MPC tool is feasible for the user due to its simplicity as it provides basic ideas and does not require complex mathematics to solve it. Other than that, MPC also is rich as all basic components can be tailored to the details of the problems in hand. The practicality of MPC makes it more preferable as it is often become the resolution of problems such as satisfying control or output constraints, which helps to determine the utility of a controller. Not only it works, it also has been proven and been used in many real applications in industry where MPC is routinely and profitably employed.

In accordance to the final objective, which is to evaluate the performance of the designed controllers, the author concludes that MPC provides all the functionality needed to control an inverse response process in terms of a response time other types of controller. It is needed to optimise the operation of a multivariable process such as the EAF used for the simulation study. MPC's capability to handle constraints makes it a very attractive option to control inverse

response in industrial processes. The weights that are applied to controlled variables make it possible to assign priorities, not only based on physical considerations, but also based on financial considerations. With the aid of MPC for inverse response, not only it is useful in optimising plant operation functionally, it also can provide the functionality to optimise processes economically. For this project, other than providing a quick response time, MPC does not provide any other significant advantage over other conventional PID and SIMC controller. Hence, to obtain a good overall performance for inverse response, PID controller would be the best choice for it. However, for the response with very small amount of overshoot, SIMC is the most suitable controller to be chosen for this case.

Since there is not much attention being paid to control serious problem of inverse response process in industry, further work on analytical simulation methodology should be carried out. More research should be done in order to provide a better control system for typical inverse response processes. This project can further be continued not only for set point tracking (servo problem) but also for disturbance rejection (regulatory) problem. Other than that, the project can also be extended by using other plant models that has time delay or other order of transfer function instead of using just simple one.

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Appendices

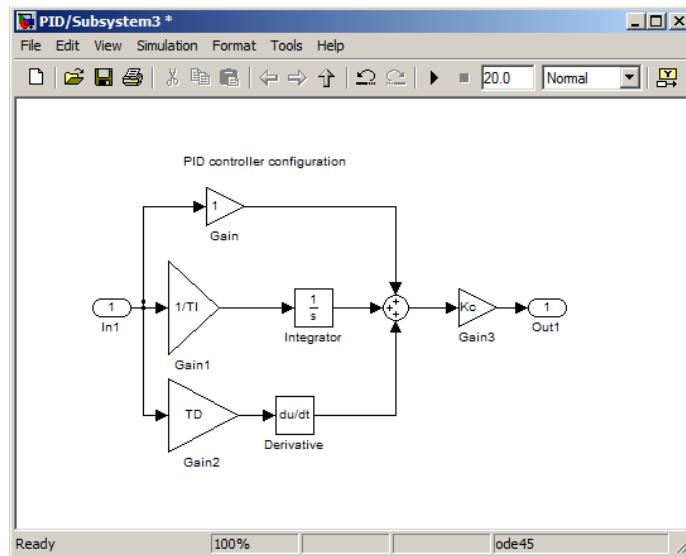


Figure 53: PID controller configuration

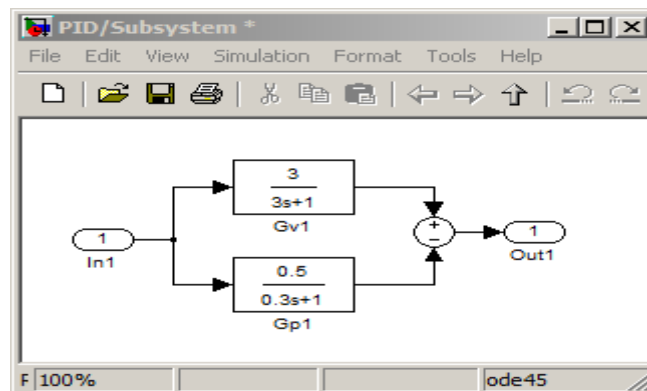


Figure 54: Inverse Response model